HOVpfs

High Occupancy Vehicle Pooled Fund Study

HOV Lane Safety Considerations Handbook

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16. Abstract
Thousands of incidents and crashes occur each year on U.S. high-occupancy vehicle (HOV) facilities, resulting in death, injury and property damage. The topic of safety on preferential facilities is especially salient given their recent growth and the numerous planning, design and operational elements that distinguish them from other transportation facilities. This handbook examines the relationship between safety on HOV lanes and variables that affect it. Its purpose is to disseminate information on HOV safety; promote integration of facility types, treatments, and practices that enhance HOV-lane safety; and raise awareness of HOV safety-research needs.

Safety considerations pertaining to a range of HOV facility types are presented in the handbook, with emphasis on common concurrent and barrier-separated designs. Guidance, best practices, and practitioner experience are assembled in an easy-to-use format for facility planning, design, operations and enforcement personnel. A general introductory/summary chapter (Chapter 2) is also provided to facilitate use of this reference guide by other audiences. Topics dealt in the handbook include safety considerations in the project-planning phase; design-related safety elements involving separation techniques, access considerations, and practitioner safety concerns; and operational practices. Safety issues associated with HOT facilities and opportunities for further HOV/HOT-safety research are also addressed in the handbook.

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CHAPTER ONE
INTRODUCTION

Welcome to the High Occupancy Vehicle (HOV)-Lane Safety Considerations Handbook.

Purpose and Goals of Handbook

This handbook serves as a comprehensive, easy-to-use reference guide for HOV-lane safety considerations. Its purpose is to provide a better understanding of HOV safety needs and improved consistency in practices that enhance HOV safety. Through a review of current guidance and operator experiences, the handbook seeks to identify and disseminate information on recommended safety practices associated with HOV facility planning, design, and operations. Safety issues concerning high occupancy toll (HOT) facilities are also addressed in the handbook.

Intended Audience and Handbook Use

The audience for this handbook includes representatives from state departments of transportation (DOTs), Metropolitan Planning Organizations (MPOs), transit agencies, enforcement agencies, and other entities responsible for the planning, design, and operation of HOV facilities. Targeted end users of the handbook include planners, engineers, managers, operations and maintenance personnel, emergency responders, enforcement officers, and other agency personnel and practitioners. The handbook is also designed to accommodate the needs of those that may be less familiar with HOV facilities and safety issues, such as public officials, members of the media, and others.

Handbook Features

The handbook includes a number of user-friendly features. The following icons are used throughout the handbook to highlight at-a-glance previews of the handbook and chapters, good ideas, keys to successful practices, and case study examples.

– This icon highlights “**At-a-Glance**” previews of the handbook and each chapter.

– This icon highlights **Good Ideas** based on experience with HOV lane safety.

– This icon highlights **Keys to Successful Practices** related to HOV lane safety.

– This icon highlights **Case Study Examples** pertaining to HOV lane safety.

To facilitate the location of information of interest, each chapter begins with a standardized introductory section providing the following information:

- Purpose/objective of chapter
- Major issues
- Context – how it relates to, builds on/toward other chapters in handbook
- Titles of remaining sections in chapter

Chapters at a Glance – Finding What You Need

This section highlights the major topics addressed in each of the handbook's chapters and appendices.

Chapter One – Introduction. This preliminary chapter helps users find information of interest by providing a summary of the development and organization of the handbook and the content of its chapters. The introductory chapter provides a succinct description of the purpose, goals, and audiences of the handbook and offers guidance regarding possible chapters of interest.

Chapter Two – Overview of HOV Facilities and Safety Considerations. The purpose of this chapter is twofold. First, it provides an overview of HOV facilities for the reader with limited HOV knowledge or experience. Second, it offers a synopsis of salient HOV safety issues that are examined in greater detail in subsequent sections of the handbook. The chapter begins with a brief discussion of the congestion problem facing metropolitan areas in the United States and the need for congestion mitigation strategies that incorporate demand management elements. The objective, function, and distribution of HOV facilities are described and the various types of HOV treatments are explained. This is followed by a brief discussion of what is meant by safety and the rationale for addressing HOV-lane safety. The chapter concludes with a summary of key safety considerations in the planning, design, and operation of HOV facilities. Readers seeking more in-depth HOV safety information may elect to go directly to relevant sections of the handbook. The section headings in this chapter are:

- The Congestion Problem
- Objective and Function of HOV Facilities
- HOV Facility Types
- What is HOV Safety?
- Importance and Challenge of Addressing HOV Safety
- Key Safety Considerations in HOV Planning, Design, and Operations

Chapter Three – Safety Considerations in HOV-Facility Planning. This chapter addresses safety considerations in the HOV planning process. It begins with an overview of the relationship between HOV planning and safety and an explanation of regional, corridor, and facility-planning efforts. The identity and broad safety responsibilities of stakeholders engaged in HOV planning are subsequently presented. This is followed by an examination safety-related performance monitoring activities to be initiated during the HOV planning stage. The conclusion of the chapter highlights safety and planning aspects of the 2002 Puget Sound HOV Evaluation in Seattle, Washington. The planning and pre-design issues addressed in this chapter provide a context for the technical design and operational safety considerations presented in the following chapters. The section headings in this chapter are:

- Overview of HOV Planning and Safety
- Stakeholders with Safety-Related Planning Roles

- Safety Considerations in the Development of HOV-Lane Performance Monitoring Programs
- Case Study: Puget Sound HOV Evaluation – Seattle, Washington

Chapter Four – Safety Considerations in HOV-Facility Design. This chapter provides an analysis of safety considerations in HOV facility design. Relevant stakeholders are identified and safety considerations pertaining to different types of HOV facilities are addressed. Geometric design standards prescribed in the American Association of State Highway and Transportation Officials (AASHTO) *Guide for High-Occupancy Vehicle Facilities* are reviewed and potential safety implications are explained. The case study at the conclusion of the chapter describes a vehicle-arresting barrier used to prevent wrong-way movements and collisions on a Dallas-area reversible HOV lane. The design-related safety considerations addressed in this chapter build on the safety planning information presented in Chapter 3 and offer a view to related operational issues that are dealt with in Chapter 5. The major section headings in this chapter are:

- Stakeholders with Safety-Related Design Roles
- Safety Considerations in HOV-Facility Design
- Case Study: Vehicle-Arresting Barrier – Dallas, Texas

Chapter Five – Safety Considerations in HOV Facility Operations. This chapter focuses on safety considerations in HOV-lane operations. The chapter begins with an introduction to key entities involved in the operation of HOV lanes. Safety considerations pertaining to stakeholder activities are described and issues relevant to specific types of HOV facilities are examined. A model HOV-lane safety evaluation program is outlined to assist operators in identifying and mitigating safety problems. The case-study synopsis at the end of the chapter highlights safety and planning lessons learned from the introduction, demise, and subsequent reintroduction of Boston's I-93 contraflow HOV lane. The operational safety issues addressed in this chapter build on the planning and design considerations dealt with in previous chapters. The major section headings in this chapter are:

- Stakeholders Involved in Safety-Related HOV-Lane Operations
- Safety Considerations in HOV-Lane Operations
- Model HOV-Lane Safety Evaluation Program for Operators
- Case Study: I-93 Contraflow HOV Lane – Boston, Massachusetts

Chapter Six – Safety Considerations in the Development of HOT Facilities. This chapter addresses unique safety-related issues associated with HOT facilities. The intent of this chapter is not to replicate general guidance related to HOT-facility development, but to highlight considerations that are relevant to safety. The issues addressed in this chapter supplement the HOV-lane safety information presented in previous chapters. Enforcement and driver-related safety concerns arising from special vehicle-occupancy determination techniques and tolling practices are examined. The case study at the end of the chapter assesses the safety benefits of the occupancy "self-declare" lane on California's State Route-91. Major section headings in this chapter are:

- Description of HOT Concept and Operations
- HOT-facility Safety Considerations
- Case Study: SR-91 Self-Declare Lane – Anaheim, California

Chapter Seven – Future Research. HOV and HOT-facility safety has received increasing attention in recent years. Nonetheless, there are many issues that either have not been adequately addressed or require further study. The relationship between safety performance of a facility and the numerous variables that can affect it is not well understood. Data and information required to draw conclusions regarding causative factors are not available or have not been collected in many cases. Practices and techniques used to analyze and address HOV and HOT-facility safety issues are sometimes incomplete or out of date. The objective of this chapter is to raise awareness of outstanding safety issues by highlighting various needs, gaps, and opportunities related to HOV and HOT safety research. The following research needs are discussed:

- Improved HOV-Lane Crash Reporting and Analysis Techniques
- Countermeasures to Address Common HOV-Lane Safety Issues
- Use of Surrogates to Identify HOV-Lane Safety Deficiencies
- Safety Impact of Opening HOV Lanes to General-Purpose Traffic During Mainlane Incidents
- Safety Impact of Opening HOV Lanes to General-Purpose Traffic During Nights and Weekends
- Safety Impact of Allowing Heavy Trucks on HOV Lanes
- Human Factors in HOV and HOT-Lane Design and Safety
- Safety Implications of HOV Resentment Among Drivers in Mainlanes
- Use of Shoulder Rumble Strips to Mitigate HOV/HOT-Facility Crashes
- Use of Glare Screens to Reduce Driver Distraction and Safety Issues
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- Speeding and HOV/HOT-Facility Safety
- Safety Performance of Radial Versus Circumferential HOV/HOT 3tFacilities
- Safety Implications of Allowing Bicycles on HOV Lanes
- Safety Considerations for HOT Facilities in Extreme Winter Conditions

Appendix A – Glossary of Terms. This appendix contains a glossary of terms associated with HOV-lane safety. It focuses on terms used in the handbook. Glossary terms included in the National Cooperative Highway Research Program (NCHRP) *HOV Systems Manual* and the AASHTO *Guide for High-Occupancy Vehicle Facilities* served as the starting point for the development of this glossary.

Appendix B – References. This appendix contains references used in the handbook. It also provides additional resources that are related to topics associated with safety on HOV facilities.

CHAPTER TWO
OVERVIEW OF HOV FACILITIES AND SAFETY CONSIDERATIONS

Introduction

The purpose of this chapter is twofold. First, it provides an overview of HOV facilities for the reader with limited HOV knowledge or experience. Second, it offers a synopsis of salient HOV safety issues that are examined in greater detail in subsequent sections of the handbook.

The chapter begins with a brief discussion of the congestion problem facing metropolitan areas in the United States and the need for congestion mitigation strategies that incorporate demand management elements. The objective, function, and distribution of HOV facilities are described and the various types of HOV treatments are explained. This is followed by a brief discussion of what is meant by safety and the rationale for addressing HOV-lane safety. The chapter concludes with a summary of key safety considerations in the planning, design, and operation of HOV facilities. Readers seeking more in-depth HOV safety information may elect to go directly to relevant sections of the handbook.

Section headings in this chapter:

- The Congestion Problem
- Objective and Function of HOV Facilities
- HOV Facility Types
- What Is HOV Safety?
- Importance and Challenge of Addressing HOV Safety
- Key Safety Considerations in HOV Planning, Design and Operations

The Congestion Problem

Traffic congestion in the United States has increased significantly in recent decades. In many areas, growth in the number of vehicles attempting to utilize roadways exceeds the resources and space available to expand them or build new facilities. Rising demand and limited roadway capacity have resulted in more frequent and longer delays for travelers and less travel time reliability. While this problem can affect communities of all sizes, it has become particularly acute in major urban areas. The growth of traffic congestion in U.S. cities from 1982 to 2002 is illustrated in Figure 2-1 on the following page.

Construction of new road infrastructure is expensive and entails right-of-way issues, vehicle emissions considerations, and other concerns that limit its potential as a congestion mitigation solution. Consequently, strategies to manage the demand for new roadway capacity have become increasingly important to the preservation of mobility in congested areas. The implementation of HOV lanes offers planners a practical alternative to the construction of additional general-purpose lanes. This is especially true when HOV options are pursued in conjunction with other congestion mitigation approaches. The ability of HOV treatments to increase the person-movement capacity of roadways has made them a vital demand management tool in congested corridors throughout the United States over the past 35 years.

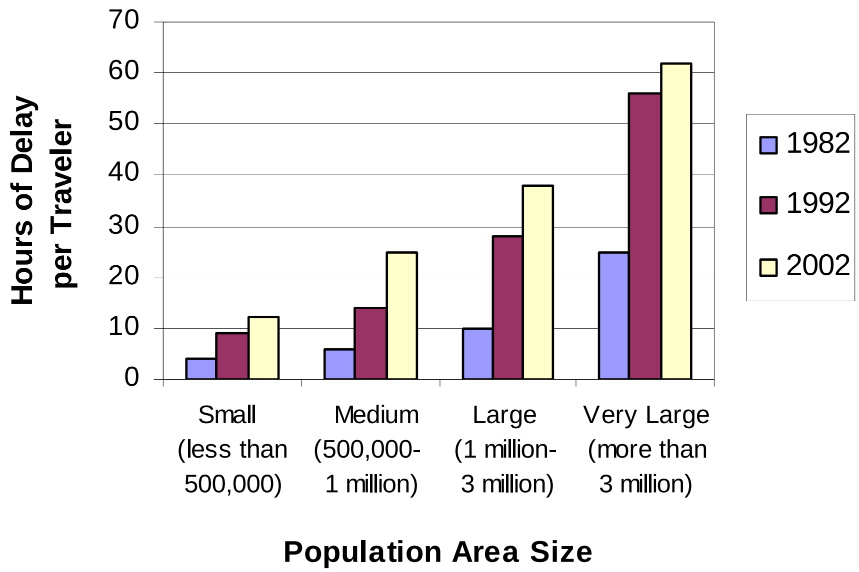


Figure 2-1. Congestion Growth Trend.[1]

Objective and Function of HOV Facilities

HOV facilities are implemented to accomplish a number of inter-related objectives. While the stated goals of individual facilities may vary slightly according to local considerations, they often include some or all of the following:

- Increase the average number of occupants per vehicle
- Provide travel time savings for multi-person vehicles
- Provide more reliable and predictable travel times for multi-person vehicles
- Preserve or improve the overall person-moving capacity of the roadway
- Improve bus operations
- Reduce transportation-related fuel consumption and pollution
- Enhance transportation options
- Reduce transportation costs

HOV facilities are able to increase the person-movement capacity of a roadway by encouraging motorists that drive alone to travel in carpools or use other multi-person transportation options such as vanpools or buses. The introduction of an HOV lane on a congested roadway creates ride-sharing incentives by offering occupants of multi-person vehicles the opportunity to bypass congestion on general-purpose lanes. Carpools, vanpools, and buses that use HOV lanes benefit from both travel time savings and more predictable travel times. Ridesharing also reduces vehicle operation expenses and improves air quality. Because the majority of vehicles on U.S. roadways have only one occupant, significant potential exists for conversion to higher-occupancy modes of travel. Figure 2-2 illustrates the impact that various ridesharing alternatives can have on the number of vehicles on a roadway.

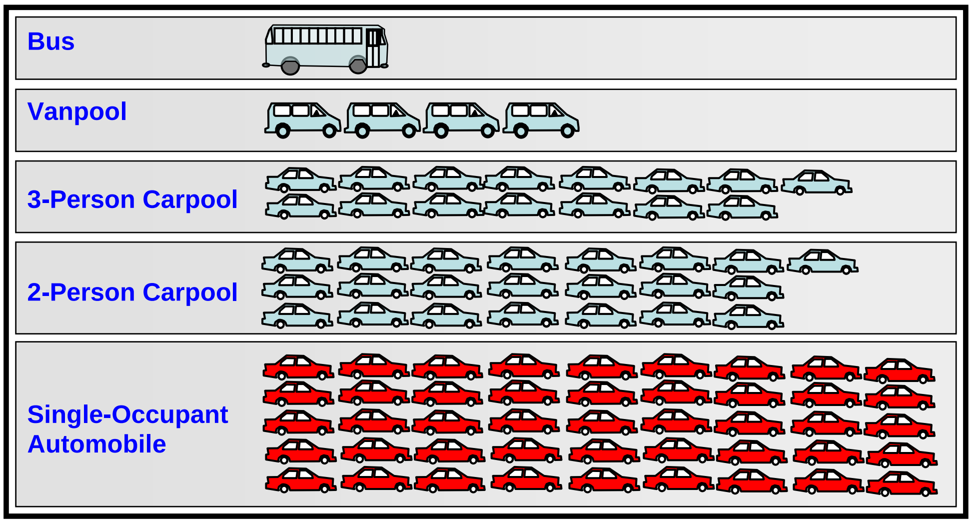


Figure 2-2. Number of Vehicles Needed to Carry 45 People.[2]

When the driver of a single-occupant vehicle (SOV) takes a bus or joins a carpool or vanpool, the roadway's person-movement capacity and efficiency increase and overall vehicular congestion declines. HOV lanes often carry several times as many people as adjacent general-purpose lanes during peak traffic hours, even though they may appear to be underutilized. This is due to higher vehicle-occupancy rates and more free-flowing traffic conditions in the HOV lane. However, not all multi-person vehicles automatically qualify for HOV facilities. Eligibility requirements for an HOV facility are determined by various factors, including:

- Specific project characteristics
- Average vehicle occupancies in the corridor
- Objectives of oversight entities at the local, state, and federal level

Minimum vehicle-occupancy requirements are established to prevent overcrowding of the HOV facility and erosion of the benefits it was designed to confer upon users. Increasing congestion on an HOV lane may warrant higher vehicle-occupancy requirements during peak traffic periods. But planners must exercise caution in establishing HOV eligibility rules. Overly stringent vehicle-occupancy regulations can be detrimental to the performance of an HOV lane. If the number of required occupants per vehicle is set too high, there may be insufficient demand and public support to justify the facility. Vehicle-occupancy provisions serve to maintain free-flow traffic conditions and maximize person throughput by balancing capacity and demand on the HOV facility.

Eligibility rules for HOV facilities are commonly expressed in the following terms and are communicated to motorists through roadway signage and HOV marketing materials:

- HOV2+: a minimum of two people per vehicle is required
- HOV3+: at least three occupants must be traveling in each vehicle

With few exceptions, single-occupant vehicles are prohibited from traveling on HOV facilities. Heavy trucks and vehicles towing trailers are also normally restricted from HOV lanes, regardless of the number occupants they are carrying. These regulations are enforced by officers stationed on or around HOV facilities. Violators may be subject to fines, license demerits, and other penalties. Most HOV facilities are either designated as exclusive busways or require eligible vehicles to carry a minimum of two or three occupants. The age of occupants is immaterial to satisfaction of occupancy requirements.

Currently, there is only one HOV4+ facility operating in the United States. It is a queue-bypass facility on Interstate 5 south of San Diego at the Mexican port-of-entry plaza.

Some HOV lanes have variable vehicle-occupancy requirements that oblige vehicles that use the facility during peak periods to carry more occupants than during off-peak periods. All HOV operators grant vehicle-occupancy and eligibility exemptions to specific classes of vehicles. These include vehicles involved in the operation or maintenance of the facility, on-duty law enforcement and emergency response vehicles, and empty buses. Some facilities also grant exemptions to motorcycles, taxis, and special low-emitting vehicles.

Growth in HOV Facilities

The first HOV facility in the United States was an exclusive busway opened on the Shirley Highway in the Northern Virginia/Washington DC area in 1969. Inauguration of this project was followed by relatively modest growth in HOV facilities throughout the 1970s and early 1980s. Over the past 20 years, a proliferation of HOV facilities and lane miles has occurred in the United States. Some 150 HOV facilities are now operated nationwide and additional projects are in the study, planning, or construction phases. Figure 2-3 shows the distribution of existing freeway HOV facilities in North America as of January 2005.

Figure 2-3. U.S. Metropolitan Areas with Freeway HOV Facilities.[3]

Internationally, HOV facilities have been introduced in Australia, Canada, and a number of countries in Europe, Africa, and Asia. All of these facilities share the goals of increasing the person-movement capacity of congested roadways and providing faster, more reliable trips to multi-person vehicles. Various types of HOV facilities have been implemented to achieve these goals.

HOV Facility Types

HOV facilities can be broadly grouped according to their application on freeways or arterial streets. The type of HOV facility adopted is a function of planning, design, and operational considerations as well as the priorities and objectives of project stakeholders. Facility options are frequently limited by spatial and financial constraints or specific challenges associated with candidate sites. This section offers concise descriptions of various types of freeway and arterial HOV facilities presently operated in the United States.

The descriptions provided below are supplemented with schematic diagrams and photos (Figures 2-4 to 2-12) that illustrate each facility type and facilitate an understanding of their application and operation.

Some of the most common types of HOV facilities in the United States:

- Freeway facilities
  - HOV lanes in separate rights of way
  - Reversible and two-way barrier-separated HOV lanes
  - Concurrent buffer-separated and non-separated HOV lanes
  - Contraflow HOV lanes
  - Queue bypass HOV lanes
- Arterial facilities
  - Bus-only lanes and HOV lanes

HOV Lanes in Separate Rights of Way

HOV lanes located in separate rights-of-way are physically isolated from the freeway general-purpose lanes. This type of facility is sometimes referred to as a busway or transitway because it is often reserved for the exclusive use of buses or buses and specified HOV vehicles. Due to their location in separate rights of way, these facilities can require considerable space and be costly to implement. They are typically designed as two-lane, two-directional facilities (see Figure 2-4) and are used in niche applications characterized by dense bus traffic. HOV facilities in separate rights-of-way are relatively uncommon in the United States. Existing facilities include the University of Minnesota Intercampus Busway in Minneapolis-St. Paul, the southwest corridor busway in Miami, Florida, and the West Busway in Pittsburgh, Pennsylvania. The primary safety considerations associated with this type of HOV facility involve separation of opposing traffic flows and prevention of wrong-way movements.

Reversible and Two-Way Barrier-Separated HOV Lanes

Barrier-separated HOV lanes are HOV facilities that are located within the freeway right of way. These facilities are generally constructed in the median, are physically separated from the general-purpose lanes by permanent concrete barriers, and are open to a broad range of high-occupancy vehicles. They are usually characterized by one or two reversible lanes that operate in the peak-period direction of travel (see Figure 2-5), but also include two-lane, two-directional facilities. Radial corridors with significant directional splits in peak traffic flows are often suitable candidates for reversible HOV facilities. Due to the limited number of access points along their length, they provide efficient line-haul transportation options for commuters in congested freeway corridors. Barrier-separated HOV lanes normally involve higher infrastructure and operating costs than concurrent lanes. There are approximately two dozen freeway HOV lanes of this type in the United States, half of which are located in the Seattle, Washington, and Houston, Texas metropolitan areas. Key safety considerations associated with barrier-separated HOV lanes include facility shoulder widths to accommodate disabled vehicles, access location and design, and separation of opposing traffic flows on two-way facilities.

Concurrent Buffer-Separated and Non-Separated HOV Lanes

Concurrent HOV lanes are facilities that operate in the same direction as the adjacent general-purpose lanes and are not physically separated from them. In a freeway setting, they provide a designated lane of travel (usually the inside, or left, lane) for high-occupancy vehicles during all or part of the day. Concurrent HOV lanes operate in the same direction as the general-purpose lanes, are typically open to a wide range of high-occupancy vehicles, and are classified as either buffer-separated or non-separated. Many buffer-separated facilities are operated as exclusive HOV lanes and are delineated from adjacent lanes with double striping and additional spacing (see Figure 2-6). Where buffer width between striping is minimal, operational characteristics of this type of facility may more closely resemble a non-separated HOV lane (see Figure 2-7). Buffer-separated facilities can either provide unlimited or designated access. Non-separated HOV lanes often revert back to general-purpose use during off-peak periods and may only be delineated by single skip striping (see Figure 2-8). The absence of ingress/egress restrictions permits eligible vehicles to move freely between the HOV facility and adjacent general-purpose lanes. Concurrent HOV lanes are the most common type of freeway HOV facility in the United States and they vary widely with respect to size, cost, and delineation techniques. Prominent safety considerations associated with them include contrasting speeds between adjoining traffic flows (speed differential), adequacy of shoulder widths, access location and design, buffer treatments, and enforcement-related challenges.

Contraflow HOV Lanes

Contraflow HOV lanes are located within the freeway right-of-way and require a significant directional split in peak-period traffic flows in order to be viable. If this condition exists and there is persistent excess roadway capacity in the off-peak direction of travel, a contraflow lane may be implemented to utilize this capacity. The contraflow lane diverts traffic traveling in the peak direction into a designated lane in the off-peak direction. Because vehicles in the contraflow lane are traveling against the flow of traffic in the remaining off-peak general-purpose lanes, changeable treatments are normally used for temporary lane separation. These include moveable concrete barriers or plastic pylons (see Figures 2-9 and 2-10). Contraflow facilities separated by plastic pylons are sometimes restricted to professionally trained drivers such as bus drivers. Moveable-barrier facilities are slightly more common and are usually open to buses, vanpools, and carpools. While freeway contraflow lanes are among the least expensive HOV facilities to implement, they are the most costly and complex to operate and maintain. Examples of moveable-barrier contraflow HOV lanes include the East R.L Thornton Freeway in Dallas, Texas, and the Southeast Expressway in Boston, Massachusetts. Among the safety considerations associated with contraflow HOV lanes are the prevention of wrong-way movements/crashes, facility setup and removal procedures, and potential access limitations and incident management challenges.

Queue Bypass HOV Facilities

Unlike the line-haul HOV lanes described above, queue bypass facilities are designed to enable buses, vanpools, and carpools to circumvent congestion at a specific location such as a freeway ramp meter. The purpose of ramp metering is to regulate the flow of vehicles entering the corridor, thereby mitigating downstream congestion. Non-HOV traffic is allowed onto the freeway at timed intervals that are signaled by a traffic light (see Figure 2-11). The provision of a queue bypass lane at ramp meters enables high-occupancy vehicles to avoid congestion and delays at these bottlenecks. HOVs are either granted unimpeded access to the freeway or are metered at a preferential rate over non-HOV traffic. Queue bypasses are relatively easy and inexpensive to implement on freeway ramps and have also been utilized to expedite HOV traffic at toll plazas. Queue bypass facilities can be found in several U.S. urban corridors, but have been implemented most extensively in Minneapolis-St. Paul area. Safety considerations associated with this type of HOV facility include the location and design of queue bypasses, speed differentials between queue bypass and regular lanes, and merging and weaving maneuvers around the facility.

Arterial Bus-Only and HOV Lanes

Numerous arterial HOV facilities are currently operated in the United States. While the functions of some of these facilities mirror those of their freeway counterparts, there are also many differences. Arterial-street HOV lanes differ from freeway HOV applications in that they:

- Serve short trips
- Operate at slower speeds
- Are rarely physically separated from adjacent traffic flows
- Provide access to local streets
- May be open to bicycle traffic

These facilities are also characterized by increased interaction between HOV vehicles, non-HOV vehicles, and pedestrians due to the presence of intersections, crosswalks, driveway access points, and on-street parking. Most arterial facilities are located in the right-side (curb) lane to facilitate bus operations. They often operate only during the peak traffic periods and are delineated by solid or skip striping (see Figure 2-12). Some arterial facilities in congested downtown areas are open to buses only, while other arterial HOV lanes are HOV3+ or HOV2+. Unlike freeway HOV lanes, some arterial HOV lanes are open to bicycles. Arterial bus-only and HOV lanes are normally implemented by rededicating an existing lane as opposed to adding a new one. Facilities developed in this manner are relatively inexpensive and can be implemented quickly. Examples of arterial-street HOV lanes can be found in California, Seattle, and a number of other areas. The primary safety considerations associated with these facilities involve lane width, potential conflicts with pedestrian and bicycle traffic, on-street parking, and turning movements.

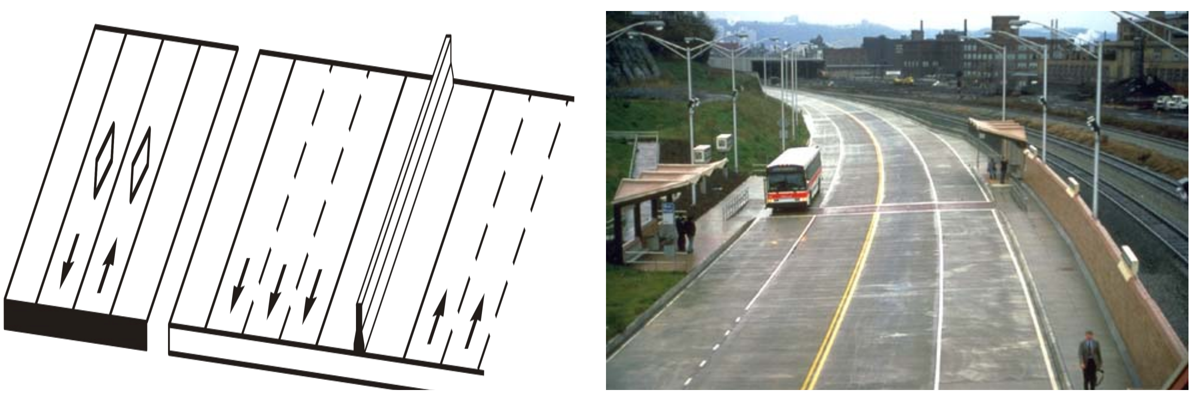


Figure 2-4. HOV Facility in a Separate Right-of-way (With Passing Lane at Transit Stop).

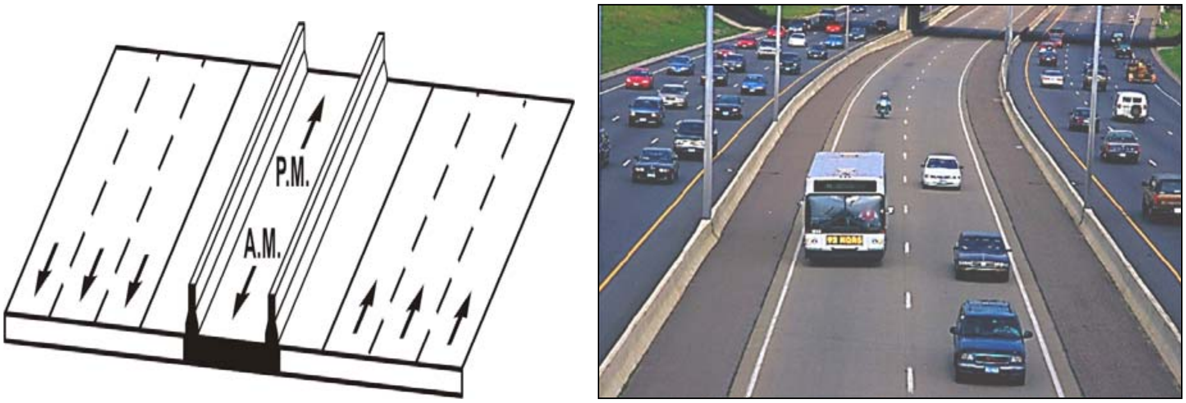


Figure 2-5. Reversible Barrier-Separated HOV Facility (Two Lane).

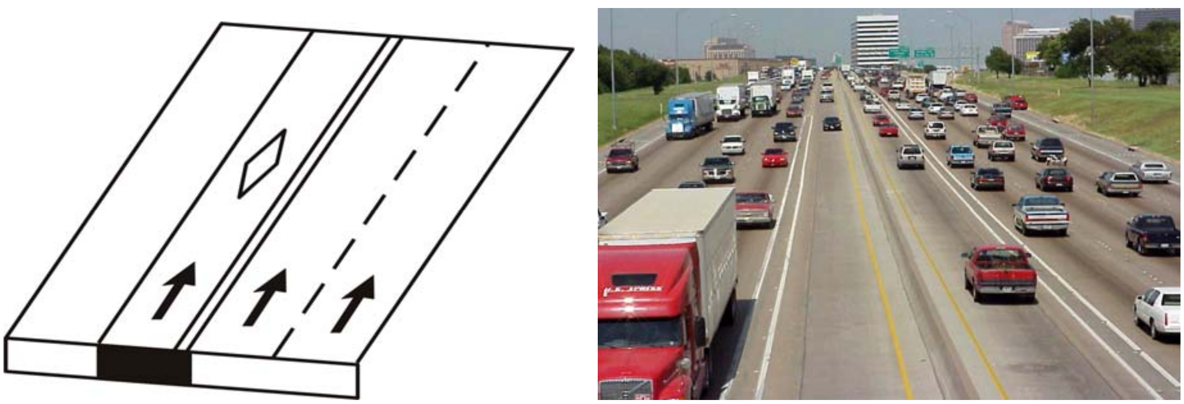


Figure 2-6. Concurrent Buffer-Separated HOV Facility (Limited Access).

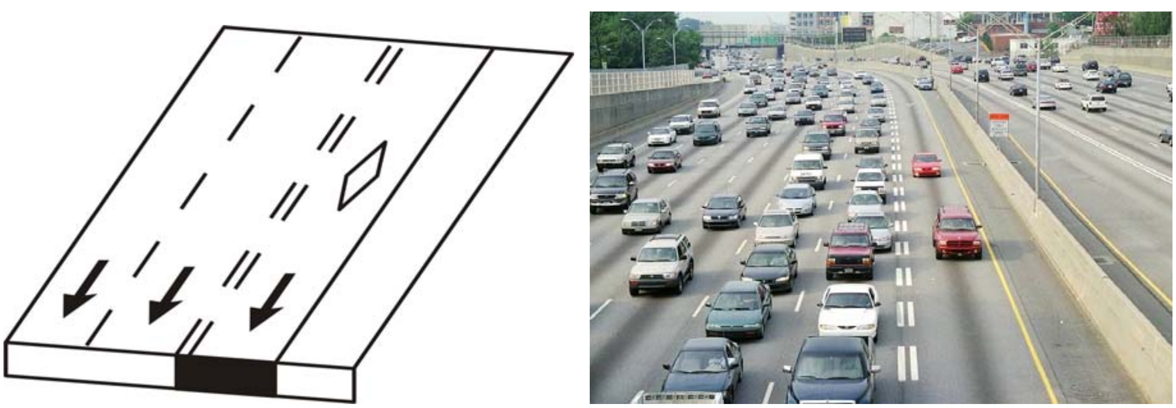


Figure 2-7. Concurrent Buffer-Separated HOV Facility (Unlimited Access).

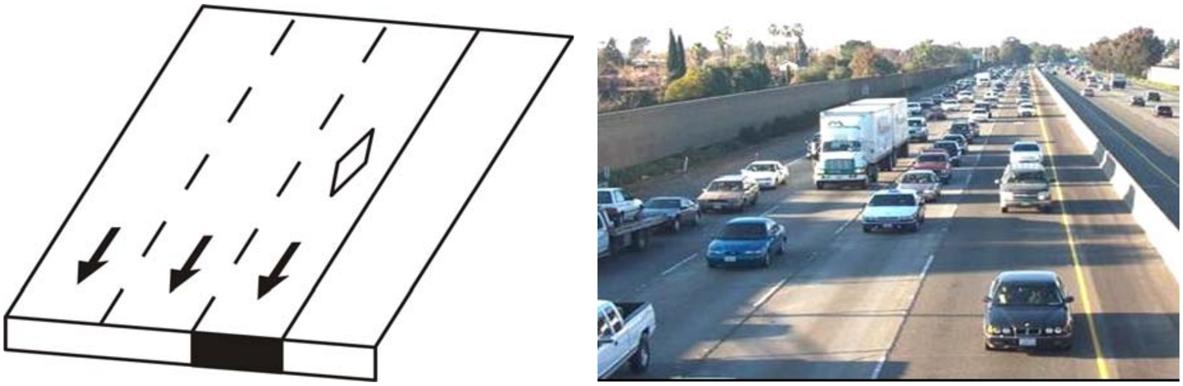


Figure 2-8. Concurrent Non-Separated HOV Facility (Unlimited Access).

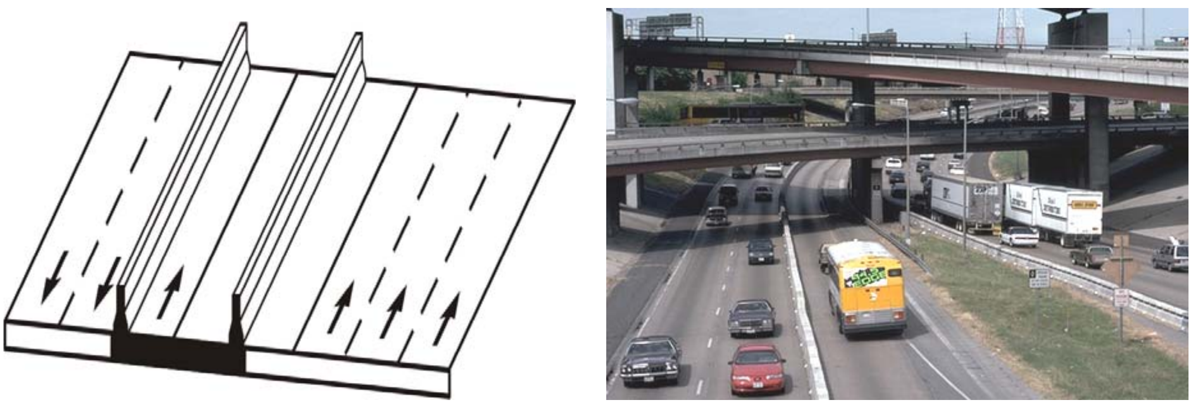


Figure 2-9. Contraflow Barrier-Separated HOV Facility.

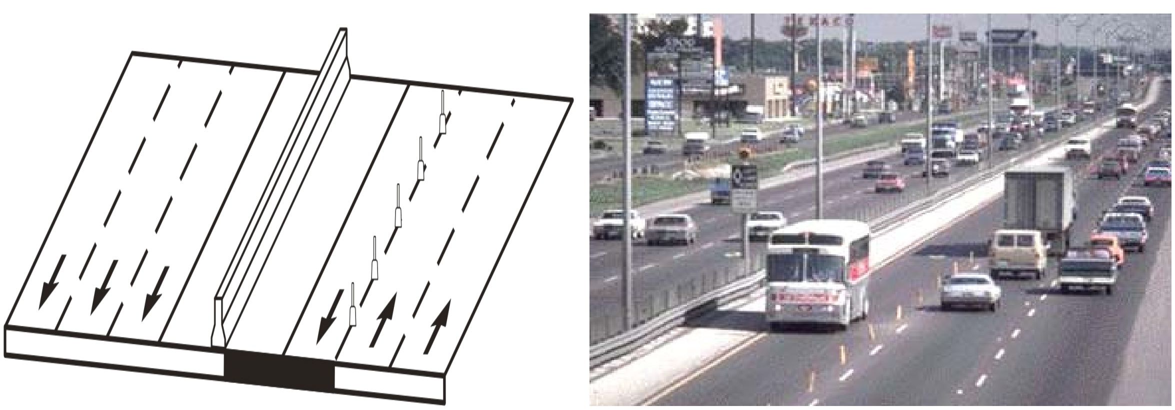


Figure 2-10. Contraflow Buffer-Separated HOV Facility (Flexible Tubular Markers).

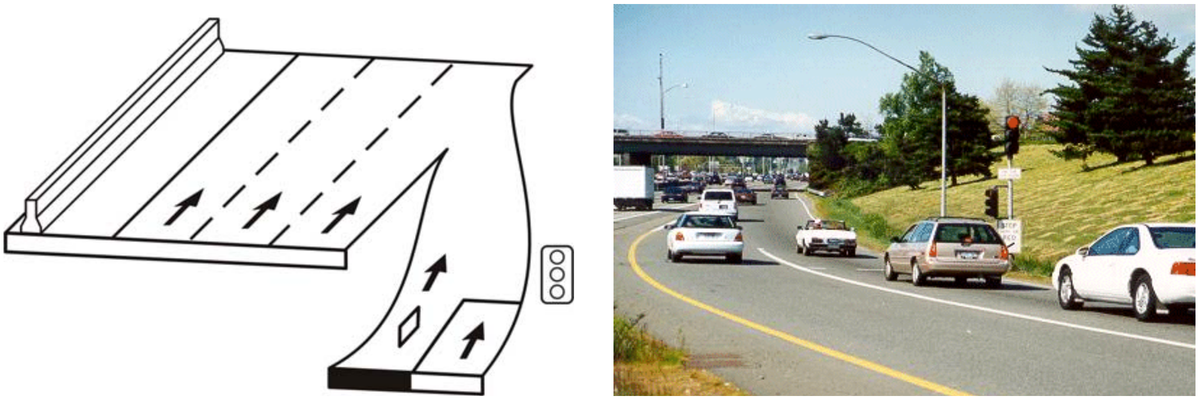


Figure 2-11. Queue Bypass HOV Facility.

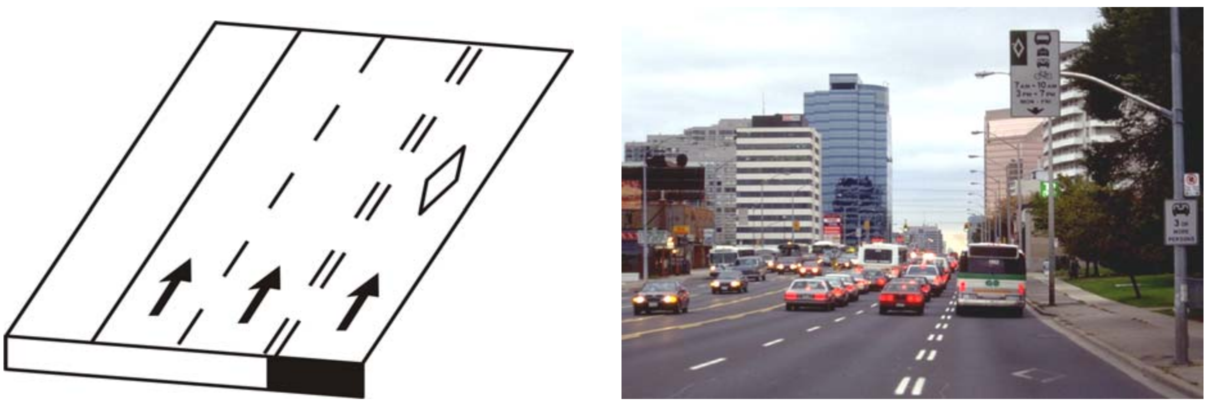


Figure 2-12. Arterial HOV Facility.

What is HOV Safety?

The concept of roadway safety can be interpreted in different ways. A brief explanation of the meaning of safety and HOV crashes in the context of this document is helpful before proceeding. In order to maximize the value of the handbook to target audiences, a broad definition of safety has been adopted. Safety considerations addressed include planning elements, policies, actions, design standards, treatments, and operational practices that have been employed by agencies to reduce the number and consequences of HOV-lane collisions and incidents. Some approaches to HOV-lane planning, design, and operations have been detrimental to facility safety. These approaches can also provide valuable insight and are highlighted where they clearly illustrate safety lessons learned.

A broad definition of safety has been adopted in order to maximize the value of the handbook to target audiences.

For the purposes of this handbook, an HOV-lane crash is defined as a collision that occurs between the milepost markers associated with the HOV facility, on the designated HOV lane or an adjacent shoulder. HOV-related crashes encompass collisions occurring on adjacent general-purpose lanes that are fully or partially attributable to HOV operations. These concepts are important in identifying HOV-lane crash rates and safety issues. Guidance presented in the handbook is also based on qualitative information assembled from published sources and experiences reported by HOV-facility operators. The decision to supplement quantitative analyses with qualitative information was the result of various factors:

- A large number of variables can affect HOV-lane crashes. These include design factors (e.g., shoulder widths, buffer widths, buffer and barrier types, access locations) and operational factors (including enforcement levels, incident and crash reporting and management, facility maintenance). The relationship between many of these variables and HOV-facility safety involves challenging quantitative assessments that have not been routinely performed on some existing HOV facilities.

- Several years of data collection may be required to draw definitive conclusions regarding causative factors influencing the safety of HOV facilities. Until more detailed studies are conducted and predictive procedures are developed, the best available information may be qualitative in nature.

- Rather than limit the scope and potential value of the handbook, qualitative information has been included where appropriate. This approach results in a more comprehensive document that addresses conventional design issues as well as more subtle safety concerns related to HOV-lane planning and operations.

Importance and Challenge of Addressing HOV Safety

Motor vehicle crash rates in the United States have declined for decades. The establishment of uniform roadway design and operational standards has contributed to this achievement. But data indicate that the rate at which motor vehicle crashes are decreasing has slowed in recent years[4]. Notwithstanding safety advances, motor vehicle crashes remain the leading cause of death for ages 3 through 33[5]. Worsening traffic congestion and an expanding population of elderly drivers underscore the importance of continued analysis and improvement of road safety techniques. This is particularly true with respect to burgeoning HOV and HOT networks, whose operations are affected by congestion and can present complex driving situations to motorists.

Thousands of crashes occur each year on U.S. HOV facilities, resulting in death, injury, and property damage. Reducing these crashes entails the identification and integration of safety "best practices" into HOV-lane planning, design, and operations. While safety is often cited as a top priority in transportation projects, it is only one of many concerns competing for limited resources and attention. Costs, physical constraints, or operational issues may preclude adoption of the "safest" HOV facility or practice in a given circumstance. In some cases, mobility and safety goals may conflict. The challenge for HOV planners, designers, and other key project stakeholders is to achieve the highest possible level of safety within the physical, financial, and operational constraints of the project[4].

A number of stakeholders are involved in the planning, design, construction, operation, and maintenance of HOV facilities. These include a wide range of federal, state, and local entities. Safety considerations may be overlooked or diluted in the complicated stakeholder tasks and interactions required to develop HOV lanes. Facilities that meet minimum geometric design standards may be assumed to be safe in the absence of obvious evidence to the contrary. However, there is increasing awareness among transportation professionals regarding the need for better HOV safety information and more explicit consideration of safety consequences in planning, design, and operational decisions. Stakeholders must understand the operational and design context that allows HOV facilities to operate safely rather than developing HOV facilities that appear to be a low-cost solution or can be made to fit an existing cross section[6]. The following sections of the handbook seek to address these needs. The safety considerations highlighted below have been distilled from more detailed guidance contained in subsequent sections of the handbook. The information presented is intended to serve as a general summary of the main chapters in the handbook, highlighting safety considerations related to HOV-facility planning, design, and operations.

HOV-Lane Safety Analysis Challenges

Several issues affect HOV-lane safety analysis. Historically, crashes on HOV facilities have not been well documented or consistently classified. Some safety evaluations of HOV lanes have been compromised due to the quality and quantity of crash data available to researchers. This has occasionally produced inconclusive or contradictory findings with respect to the safety of specific HOV-lane policies and treatments. If an HOV facility is suspected of being less safe than an alternative design or conditions prior to the facility's implementation, there may be reluctance on the part of project stakeholders to publicize safety information. Even HOV facilities that meet or exceed geometric design standards may exhibit high crash rates, frequencies, and severities. Developing an understanding of the factors affecting HOV safety is an important and challenging task.

Summary of Safety Considerations in HOV-Lane Planning

HOV-lane planning activities occur at the regional, corridor, and facility levels and often take years to complete. The incorporation of safety considerations into the HOV-planning process and its subsequent impact on HOV design and operations is illustrated in Figure 2-13.

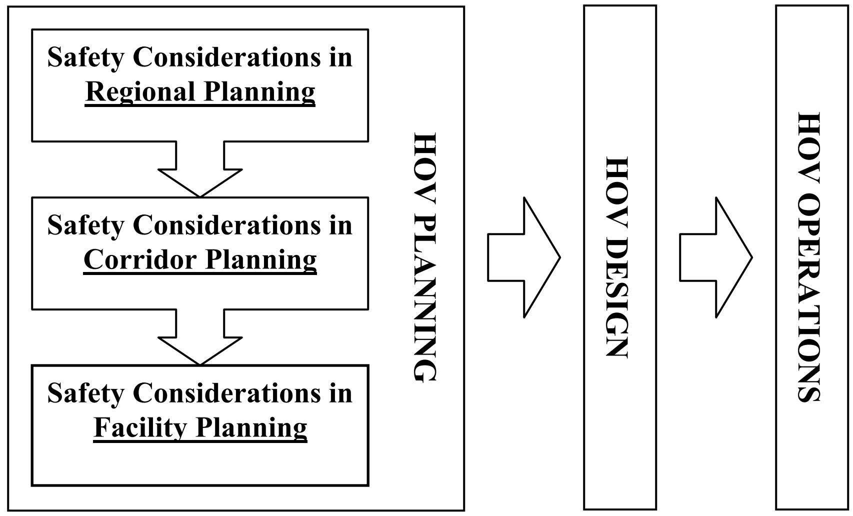


Figure 2-13. Development and Impact of Safety Considerations in HOV Planning.

The extent of the planning process depends upon a number of factors but is generally commensurate with project complexity. While there is no systematic method for integrating safety into the planning process for every type of HOV facility, safety considerations can and should be addressed at the HOV-lane planning stage. This raises the profile of safety issues among project stakeholders, enables subsequent safety-related analyses, and promotes a proactive rather than reactive approach to facility safety. Benefits of this strategy include:

- Fewer inappropriate HOV-facility locations, types, designs, and operations
- Reduction of inherently unsafe conditions on and around HOV facilities
- Prevention of HOV-facility crashes and related deaths, injuries, and property damage

Failure to adequately address safety in HOV-lane planning can jeopardize the success of the project. For example, inadequate involvement of law enforcement agencies in project planning efforts may result in a shortfall of enforcement resources or the selection of a corridor or facility type that is difficult or dangerous to enforce. Such problems can lead to inadequate enforcement and high violation and crash rates that, in turn, generate public and political opposition to the facility. To avoid these problems, all relevant stakeholders should be involved in HOV-lane planning activities and be given a voice in decisions regarding project development.

Crash Data and Performance Monitoring

A key safety issue in HOV-lane planning concerns data. HOV-facility implementation has positively impacted the safety of some corridors and negatively affected others. However, insufficient data regarding crash rates prior to the implementation of an HOV lane frustrates subsequent attempts to understand the safety implications of the project. During the planning process, the safety of a proposed HOV corridor should be monitored on a lane-by-lane basis so that distinctions in crash rates and traffic mix/flow characteristics are accounted for. Safety metrics applied at the planning level enable valid comparisons of "before-and-after" data and quantification of the safety impact of HOV-lane implementation. These data also provide valuable insight into the underlying reasons for a facility's safety performance and the potential need for design or operational changes to address adverse safety conditions or impacts. Through crash data analysis, differences in before and after crash rates may be traced to specific changes in traffic flow patterns and congestion. Changes in the type, volume and speed of vehicles are identifiable and more valid "apples to apples" safety comparisons can be made.

The establishment of a performance monitoring program and the collection of baseline safety data for a proposed HOV corridor should be undertaken years prior to the start of HOV-lane construction. Safety-related elements in the development and implementation of a performance monitoring program are shown in Figure 2-14.

Identify Safety Goals and Objectives
↓
Identify Safety Measures of Effectiveness
↓
Identify Safety Data Requirements
↓
Collect Safety Data
↓
Analyze Safety Data
↓
Report Safety Results – Modify Operations As Needed

Figure 2-14. Safety Elements in HOV-Lane Performance Monitoring Programs[3].

The first four safety elements in this program are conducted during the HOV-planning process. The following highlight examples that may be developed for each of these steps:

Identify Safety Goals and Objectives

Identification of safety-related goals and objectives is the first step in HOV performance monitoring. Safety goals are general project intentions expressed as succinct statements that emphasize safety issues among other project considerations. These goals serve to identify safety as a project priority and advance safety issues throughout HOV development. An example of a safety goal for an HOV facility might be:

- Develop and implement an HOV facility that provides a safe transportation option.

At the corridor and facility-planning levels, project stakeholders refine the safety goal(s) into more detailed and targeted objectives. Objectives define a desired result and may include specific actions and time frames. The following objectives apply to the above-mentioned safety goal:

- Implement the HOV lane within five years without increasing crash rates on adjacent general-purpose lanes.

- Maintain HOV-lane crash rates at a level equivalent to or lower than adjacent general-purpose lanes.

Identify Safety Measures of Effectiveness

Measures of effectiveness (MOEs) provide a means for undertaking quantitative safety analysis and assessing whether safety objectives have been met. Each objective may have one or more corresponding MOE. These measures should be precise and focus on the core elements of their respective objectives. Examples of MOEs that correspond to the safety objectives listed above are:

- Number, type, severity, and location of crashes for the HOV lane and each adjacent general-purpose lane

- Crash rates per million vehicle-kilometers or vehicle-miles traveled (VKT or VMT)on the HOV lane and each adjacent general-purpose lane

- Crash rates per million passenger-kilometers (or miles) traveled on the HOV lane and each adjacent general-purpose lane

Identify Safety Data Requirements

The identification of safety data needs flows directly from the previous step. Data requirements for each MOE should be unambiguous and the method of collecting and analyzing the data should be clear. For example, determination of crash characteristics on HOV and general-purpose lanes requires access to detailed law-enforcement crash records. In order to ascertain crash rates per million vehicle-kilometers (or miles) of travel, information on traffic volumes is needed. Calculation of crash rates per million passenger-kilometers (or miles) of travel entails manual collection of vehicle-occupancy data. This information must be gathered regularly and reported in an accurate and standardized fashion so that credible analyses and comparisons can be made.

Collect Safety Data

Baseline safety data must be collected for two or three years in advance of HOV-lane construction to permit meaningful before-and-after comparisons. The collection of safety data should begin in the project planning phase, be maintained throughout HOV-lane design and construction, and continue on an ongoing basis once the facility is operational. Diverse techniques are employed in the collection of safety data, including:

- Manual observation/counts of vehicle types and occupancy levels
- Electronic collection of traffic volume information using loop detectors, automatic vehicle identification (AVI) systems, electronic toll collection technology, and other means
- Review of electronic and hard-copy crash data and reports prepared and coded by law enforcement and motor vehicle safety agencies

The remaining safety steps in the program (analysis and reporting of safety information) are conducted on an ongoing basis throughout project planning and implementation.

Summary of Safety Considerations in HOV-Lane Design

The design of a road can have a profound effect on the actions and safety of road users. Crashes occur due to the failure of road users to successfully negotiate the road environment. While this is sometimes due to driver issues such as inattention, impairment or violation of regulations, it can also be influenced by facility design. The process of designing an HOV lane flows from the planning phase in which a specific facility type is selected. Safety-related design issues encompass:

- Lane and shoulder widths
- Provision and design of buffers
- Delineation and separation techniques
- Access treatments and signage
- Enforcement-site location and design

This section highlights salient safety considerations related to common HOV facility types.

General Access Considerations

Ingress and egress treatments are the design features that enable vehicles to enter and exit limited-access HOV lanes. They are fundamental to the design of HOV lanes and can have a significant effect on vehicle conflicts. Crash “hot spots” along

HOV facilities are frequently located in the vicinity of access points due to the merging, weaving, congestion, and speed differentials that are prevalent there. Limited-access HOV facilities with numerous intermediate ingress and egress sites may be especially vulnerable to these are related safety problems. The following points highlight general safety-related considerations pertaining to HOV ingress and egress design (adapted from[6, 7, 8]):

- Where possible, the same geometric criteria should be applied as would be used for a freeway ramp, including locally recognized entrance and exit standards. HOV-lane ramps should be designed to the acceleration and deceleration characteristics of loaded buses. Very long, gradual tapers should be avoided on exit ramps, as traffic may inadvertently follow the taper assuming it is the main roadway.

- Sight distance is particularly critical due to the proximity of barriers to ramp-lane alignments. Lateral clearances are often no greater than 0.6 m (2 ft) from the edge of the travel lane to the barrier. Where practical, removal of barrier-mounted glare screens that reduce sight distance or slight adjustments in striping alignment may be necessary within the ramp envelope to accommodate the proper design speed.

- The location of ingress/egress facilities is influenced by a number of factors. For example, direct access ramps to/from local streets should be made with candidate streets that currently do not have freeway access, so as to better distribute demand and prevent overloading existing intersections. For at-grade access with the adjacent freeway lanes, designated outlets should be strategically positioned so as to prevent significant weaving conflicts across freeway lanes.

- A freeway lane should not turn into an HOV-lane; the HOV lane should be located out of the normal path of travel. Motorists desiring ingress to the HOV facility from a freeway lane should be required to make an overt maneuver. Similarly, intermediate HOV off-ramps should be designed so that an overt maneuver is required to exit the facility and HOV through traffic is not inadvertently exited.

- HOV-lane access ramps should provide adequate space for possible metering and storage.

- Single HOV lanes do not allow for passing or lane changes within the facility. Left- or right-hand exits from a single-lane HOV lane are equally valid and equally safe. The standard "right-hand only" rule for entrance and exit ramps should not apply for HOV lanes.

- During initial operations of new HOV facilities, demand may not warrant direct or elevated ramps. If demand subsequently increases, a retrofit design could be difficult, expensive, and require safety compromises during construction. When exclusive ramps are not included in the initial project design, provisions should be made so that the ramps can be safely added later.

- Safety lighting should be applied for all ingress/egress locations using the same warrants applied for urban freeway entrance and exit ramps.

- HOV lane drops should be avoided. Where HOV lanes are terminated by dropping either the HOV lane or a general lane, a forced merge is created. This is a hazardous condition, particularly at locations having high speed differential between the HOV lane and general travel lanes. The ideal exit terminal treatment is a continuous lane. If any lane must be dropped at the end of an HOV facility, it is preferable to drop a right lane at a high exit demand location and shift all lanes to the left.

- Weave analysis should be performed to ensure that existing and projected traffic volumes can be safely accommodated by the selected access design

General Signage Considerations

HOV-lane signage, together with pavement markings and other traffic control devices, performs an important safety function by providing travelers with information that is necessary for safe use of the facility. Lack of motorist understanding about the designation or function of an HOV facility can present serious safety issues. Consistent and frequent signage is required prior to and on HOV lanes due to the relatively large amount of information that must be conveyed to motorists. Common signage problems that can contribute to motorist confusion and HOV-lane safety issues include inconsistent signage, signage that does not adhere to established Manual on Uniform Traffic Control Devices (MUTCD) standards, and poor signage location or positioning. This underscores the importance of addressing substandard or inconsistent signage, particularly within a single region or HOV-lane network. The general guidelines below should be observed to minimize or prevent signage-related confusion, erratic maneuvers, and other safety issues from developing on HOV facilities (adapted from[9]):

- Adequate advance signage should be provided and pavement markings should be used to emphasize lane designation.

- Make regulatory signs the standard MUTCD white diamond symbol over a black background in the upper left-hand corner and black lettering on a white background for the rest of the sign. Follow standard MUTCD guidelines for color, font, and type size so that signs are easily identified and read and are not lost in clutter.

- Make guide signs the standard MUTCD white lettering on a green background. Alternatively, the use of banners and symbols may be used to help distinguish special use lanes in an environment with potential sign clutter.

- Make the sign size consistent with the speed of the traffic reading it.

- Ensure information is presented consistently: identify the lane (top line), who it applies to (second line), and applicable time of day and day of week (last line).

- Be consistent about where signs are placed (overhead or side-mounted) and at a distance that gives drivers ample time to react. Whenever possible, mount the HOV sign directly over the affected lane.

- When conveying a lot of information, the use of concisely worded signs, rather than symbols can enhance safety. Employing banners with symbols can also help distinguish special use lanes and reduce driver confusion.

- Use the diamond symbol to mark the pavement on all HOV lanes, and repaint symbols as needed.

- Use a standard signing strategy.

General Enforcement Considerations

Enforcement is an important component of HOV-lane design and operations and can have a significant impact on the success and viability of an HOV project. The enforcement-related design considerations addressed here focus specifically on safety. The term "enforcement area" is used to refer to a number of potential design treatments that provide space for police personnel to monitor an HOV facility, to pursue a violator, and to apprehend a violator and issue a ticket or a citation[6]. Depending on the type of facility in question, certain design considerations must be taken into account to protect the safety of enforcement officers, facility users, and general-purpose traffic. If these considerations are not properly accounted for in the design process, facility safety issues may arise, contributing to enforcement problems and project failure. These considerations, detailed in the facility subsections of this chapter, include:

- Consultation with enforcement personnel and agencies in the facility design process

- Additional lighting, signage, traffic control devices, and the provision of safe observer vantage points

- Minimum enforcement area width of 3.6 to 4.3 m (12 to 14 ft)

- Minimum enforcement area length of 30 m (100 ft) (dependent on facility type, traffic speeds, violation rates, and violator storage requirements)

Safety Issues Associated with Reversible Barrier-Separated Designs

The design of barrier-separated HOV facilities can have safety implications beyond those described above. Practitioners and researchers have identified safety effects specifically related to barrier-separated HOV-lane designs. These issues, summarized below, augment the safety considerations in HOV-lane operations that are examined in Chapter 5 of the handbook.

Advantages of Barrier-Separated HOV Facilities

There is a general consensus that barrier-separated HOV facilities offer critical safety advantages over buffer-separated and non-separated HOV lanes:

- Concrete barriers protect traffic in the HOV lane and general-purpose lanes from the considerable speed differential that may exist between the two traffic streams.
- Collisions that occur in the general-purpose lanes do not, therefore, typically disrupt the operation of the barrier-separated facility[7].

In 2003, a study of crash data collected before and after buffer and barrier-separated HOV lanes were implemented in Dallas, Texas, indicated that, unlike the buffer-separated lanes, the barrier-separated facility did not have a negative impact on injury crash rates[10]. A 1992 HOV-lane safety study conducted by the California Polytechnic State University reported similar findings. Crash rates were evaluated before and after installation of HOV facilities with and without physical separation. On projects where no physical separation existed between the HOV and general-purpose traffic lanes, crash levels increased dramatically during the first year of operation. These rates subsequently declined, but remained significantly higher than pre-project levels. Where the HOV lane was physically separated from the general-purpose lanes, no upward surge in crash rates was discernable[11].

Safety Disadvantage of Barrier-Separated HOV Facilities

Notwithstanding their overall superior safety performance, barrier-separated HOV lanes may also confer potential safety disadvantages in certain cases:

- The limited-access operation of barrier-separated HOV facilities concentrates weaving in the general lanes to particular locations upstream of HOV access terminals and downstream of HOV egress terminals[8]. Weaving across congested general-purpose lanes to and from these access points is a relatively complicated maneuver that degrades safety by exacerbating vehicle conflicts. This problem is applicable to barrier- and buffer-separated facilities.
- A vehicle that becomes disabled on the interior general-purpose lane may have to traverse several lanes of traffic to reach a refuge area on the right-hand shoulder of the freeway as a result of HOV-lane barrier separation.

- Close proximity of the median barrier to general-purpose traffic can lead to multiple-vehicle crashes if a vehicle strikes the wall and is deflected back into the traffic lanes[8].

- Median or lateral barriers and glare screens may obstruct sight distances around curves and at other locations. These treatments may have to be adjusted or removed in specific areas for safety purposes[12].

- The inability of a vehicle to exit a barrier-separated facility in the event of an emergency can also disrupt operations and generate secondary incidents, particularly if there is limited space within the facility.

Barrier-separated HOV lanes have many of the characteristics of a tunnel because once on the lane, vehicles must travel to the next access point before exiting. Incidents occurring in these "pipeline" sections can seriously interfere with traffic flow if roadway and shoulder widths are insufficient to allow for storage of disabled vehicles[8]. Motorists on barrier-separated facilities often travel at much higher rates of speed than vehicles in adjacent general-purpose lanes. This obliges them to react more quickly to the driving situations they are presented with. The distance needed to stop increases, and the time available for stopping or taking evasive is reduced. Driving becomes a more complex and demanding task at high speeds and the margin for making and correcting errors diminishes[13]. Because drivers in the HOV lane do not expect to encounter stopped traffic, braking and safely maneuvering around a disabled vehicle can be difficult and dangerous. Signage and enforcement should be leveraged to address excessive speed on barrier-separated HOV lanes and reduce the frequency and severity of related crashes.

The potential impact of disabled vehicles on HOV-lane safety is well recognized in the design community. The extent to which a barrier-separated HOV lane can accommodate disabled vehicles is largely a function of the availability of right of way. Figure 2-15 shows two examples of reversible barrier-separated HOV facilities built within freeway medians. The first facility was constructed in a highly constrained envelope and consists of a single reversible lane with relatively narrow shoulders. Although disabled vehicles can typically be passed on such facilities, they often pose safety hazards. Even in the absence of disabled vehicles or lane obstructions, small barrier offsets may contribute to safety issues.

Figure 2-15. Reversible Barrier-Separated HOV Lanes with Narrow (left) and Wide (right) Shoulders.

In the second example, demand and available right-of-way were sufficient to construct a two-lane reversible facility with full breakdown shoulders. The equivalent of at least one 3.0 m (10 ft) shoulder is recommended for all barrier-separated designs so that a disabled vehicle parked to one side of the facility can be passed without endangering the safety of motorists or obstructing traffic[6]. Where shoulder widths on existing facilities cannot be expanded due to right-of-way constraints, designated breakdown areas within the facility should be provided.

Safety Issues Associated with Buffer-Separated and Non-Separated Designs

Buffer-separated and non-separated HOV facilities are relatively inexpensive to implement, can be accommodated in constrained rights-of-way, and offer operational flexibility. However, their use involves special safety considerations. This section provides summary of these issues and identifies potential safety enhancements.

Buffer Separation versus Non-Separation

Buffer-separated and non-separated HOV facilities are relatively inexpensive to implement, can be accommodated in constrained rights-of-way, and offer operational flexibility. However, their use implies unique safety considerations. Buffer-separated HOV facilities may provide various safety advantages compared to non-separated HOV lanes[14]:

- Higher level of driver comfort
- Added margin of safety through extra maneuvering room
- Lessening of the impact from incidents on adjoining lanes

Overall, both buffer-separated and non-separated HOV designs are considered to be less safe than barrier-separated facilities. The distinct crash patterns exhibited on buffer-separated HOV lanes with limited access is primarily due to the concentration of merging and weaving maneuvers at access points. Crashes on non-separated HOV lanes with continuous access are typically distributed more evenly along the length of the facility. However, the absence of designated access points on these facilities may degrade safety between adjacent traffic flows by increasing the exposure and vulnerability of motorists to the effects of speed differentials during weaving maneuvers.

Buffer treatments vary according to width and design (see Figure 2-16). Buffers that are narrower than the prescribed 1.2 m (4 ft) minimum may be detrimental to safety because they can result in insufficient lateral capacity and access conflicts if vehicles traveling at different speeds are forced to share the same lane. Given the frequency and potential seriousness of sideswipe and rear-end crashes on concurrent HOV lanes, every effort must be made to ensure that facility designs incorporate features that help prevent them and the conditions that cause them.

The following recommendations address these concerns:

- The minimum cross section for a buffer-separated HOV lane provides enough room for two 2.4 m (8 ft) wide vehicles to be side by side in the HOV-lane area (inside shoulder, HOV lane, and painted buffer) without encroaching on the general-purpose lanes. This is important because it allows two vehicles with a large speed differential to avoid a collision[10].

- At-grade access points should be located strategically to minimize weaving conflicts and the formation of congestion. A weave analysis should be undertaken as part of the design process to ensure that the access treatments are safe and appropriate for anticipated traffic levels.

- Clear and redundant signs in advance of access locations and exit ramps should also be incorporated into the facility design to reduce crashes related to abrupt maneuvers.

- Although expensive, direct access ramps and freeway-to-freeway connectors can further improve HOV-lane safety by eliminating the need for traffic to weave across multiple general-purpose lanes in order to enter or exit the facility.

The minimum cross section for non-separated HOV lanes does not allow two vehicles to be side by side in the HOV area at the same time. Therefore, this design should only be used in exceptional cases, on an interim basis, and for short distances. Possible design modifications to improve the safety of substandard buffer-separated HOV lanes include retroflective tubular markers installed between the striping of the buffer. Although these flexible plastic poles can be struck by vehicles if necessary, they represent a strong visual and psychological barrier to buffer violations (see Figure 2-17).

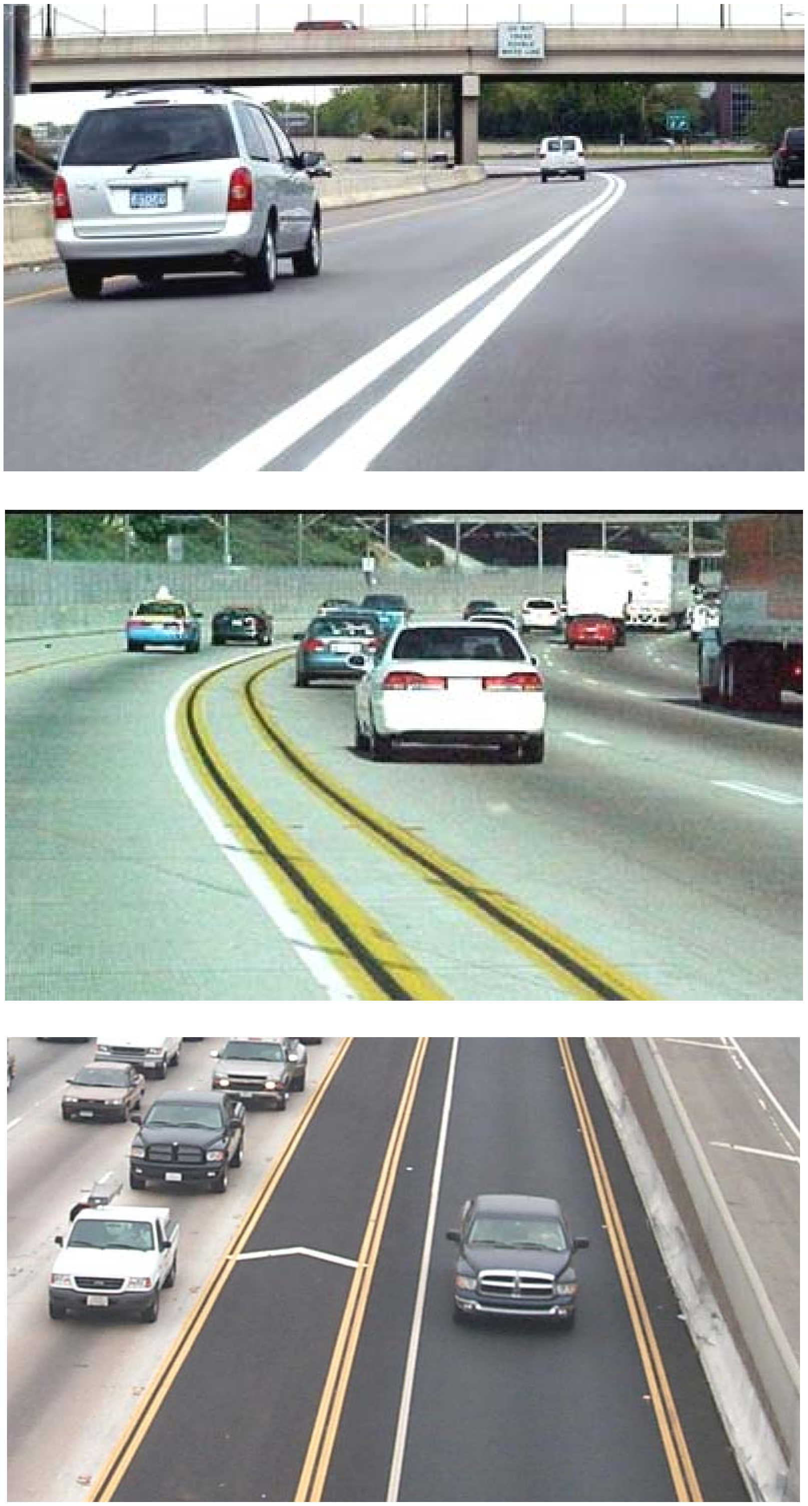


Figure 2-16. Concurrent Limited-Access HOV Lanes with Narrow (top), Medium (center), and Wide (bottom) Buffers

Figure 2-17. Flexible Tubular Markers Used to Reduce Buffer Violations

The reduction in speed differential between the HOV and adjacent lanes significantly decreases the likelihood of crashes during merge/diverge movements[15]. Large speed differentials between the HOV lane and adjacent general-purpose lanes frequently develop during peak travel times when the latter become congested. Slower vehicles must merge into a high-speed HOV lane or faster vehicles in the HOV lane must rapidly decelerate in order to merge into the general-purpose lane. This creates dangerous merging conditions that may result in a sideswipe or rear-end crash[8]. HOV facilities with buffers that are wider than the standard 1.2 m (4 ft) may offer potential safety advantages in this respect, including:

- Greater separation of traffic flows and reduced exposure to speed differentials and erratic maneuvers
- Improved driver comfort and incident isolation
- Potential for incorporating wider and longer acceleration, deceleration, and weave lanes

A quantitative analysis of the safety impact of adopting a wide buffer design as opposed to a buffer-separated design with a wide left enforcement shoulder/refuge area and a standard 1.2 m (4 ft) buffer has not been undertaken and published. However, potential negative safety impacts of this treatment over long distances could include:

- Use of the buffer as a breakdown or refuge area
- Use of the buffer for passing

Striping, appropriate pavement markings, and substantial buffer and HOV-lane violation penalties may be used to effectively counteract these problems.

Use of HOV Lane by Disabled Vehicles

Substandard inside shoulder width may cause disabled vehicles to stop on the HOV lane, either partially or completely blocking the lane. During uncongested time periods, drivers may knowingly or unwittingly park a disabled vehicle on an operating HOV lane, endangering the safety of HOVs and travelers in adjacent lanes[10]. This problem can be especially prevalent if the HOV lane has been developed using the former inside shoulder of the general-purpose lanes and is separated by a buffer that resembles an edgeline. Design techniques that counteract these safety problems include:

- Avoid differences in pavement color or texture between the HOV lane and mainlanes that can contribute to driver confusion regarding the designation of the HOV lane.

- Properly sign and mark HOV lane at regular intervals along its entire length. Signage reading "NO STOPPING THIS LANE" with an arrow directed at the HOV lane is an effective countermeasure for this problem.

- Use double solid or skipped lines to more forcefully delineate HOV facility – single line resembles edgeline and is less conspicuous (see Figure 2-18). Logitudinal joints should not conflict with lane lines and when this is unavoidable, resurfacing should be considered.

Figure 2-18. Concurrent Unlimited-Access HOV Lanes with Single (left) and Double (right) Striping

Summary of Safety Considerations in HOV-Lane Operations

Operation of an HOV lane may entail a variety of activities including daily opening and closing of the facility, reversing the direction of traffic, enforcing eligibility and occupancy requirements, managing incidents, and collecting data. This section highlights safety considerations associated with these activities and provides an overview of an HOV-lane safety evaluation program for operators.

Lane Opening, Closing, and Reversal

For most contraflow and reversible HOV lanes, opening and closing the facility entails both manual and electronic procedures. Manual placement and retrieval of traffic control devices on an HOV facility is an activity that exposes operations crews to dangerous environments. Inclement weather and darkness increase this risk by making personnel, vehicles, signage, and lane delineators more difficult to see. Special safety considerations should be incorporated into HOV-lane operations to reduce the potential for injury to operations personnel and motorists. The following safety guidelines should be observed for these procedures:

- Placement/removal of safety cones, drums, or barricades at access points are redundant safety treatments that should be used in conjunction with signage, beacons, gates, and barriers to prevent motorists from inadvertently attempting to access the facility when it is closed.

- Prior to opening the lane, it should be inspected to ensure that lane control signals, variable message signs (VMS), warning beacons, automatic swing arms, gates, barriers, and other critical equipment are functioning properly and that the lane is free of obstructions and debris.

- Barricades, cones, and temporarily deployed equipment should be removed and stored where they will not be struck or dislodged. Gates should be tightly secured so that they do not impact passing vehicles (especially important at access points characterized by reduced lane widths and barrier offsets).

- Surveillance and incident detection technologies should be utilized prior to opening the HOV facility to verify that disabled vehicles or other obstructions are not blocking the lane.

- Variable message signs and traffic control signals should be controlled by or closely coordinated and verified with operations personnel on the ground to guard against equipment malfunction.

- Traffic management center personnel that monitor facility opening and closing procedures should be authorized to prevent the HOV lane from opening if the facility cannot be safely operated.

- Moveable barriers, pylons, and tubular markers used on contraflow facilities should be deployed in the direction of the prevailing traffic.

- The removal of barriers or delineators is done in the opposite direction so that the lane reverts to normal use behind the crew.

- Safety training should be provided to all personnel deployed in the field for these operations.

- Appropriate safety equipment, such as fluorescent safety vests for operations personnel, should also be provided.

Incident Management

Incident management is the coordinated use of personnel and resources to reduce the duration and impact of traffic incidents and improve the safety of motorists, crash victims, and responders. Incidents that can affect HOV-lane operations include:

- Crashes and disabled vehicles
- Adverse weather conditions
- Debris on the roadway, spilled loads
- Equipment or infrastructure malfunction

These events impact safety by creating lane closures, blockages, and obstructions and changing the type and volume of traffic using the HOV lane. Table 2-1 presents potential stakeholders response strategies for common HOV-lane incidents.

Table 2-1. Potential Incident Response Stakeholders and Strategies[6]

Incident	Potential Response Strategies
Disabled vehicle (flat tire, run out of gas, etc.)	• Commercial towing service • Police
Disabled bus	• Transit operator tow truck and replacement bus • Commercial towing services • Police to manage traffic
Crash/no injuries	• Police • Commercial towing service
Crash/injuries	• Emergency medical services (EMS), ambulance • Police • Commercial towing service
Crash/special problems (toxic substance, etc.) or hazardous waste	• Police • Commercial towing service • Fire, EMS, or other special response team
Facility damage and/or debris	• Emergency maintenance repairs
Snow, ice, flooding, or other weather-related emergency	• Snow plows and other service vehicles • Commercial towing service

Effective use of incident management on HOV lanes enables initial events to be quickly addressed and secondary incidents to be prevented. Secondary incidents often occur due to unexpected congestion and driving conditions surrounding the initial incident. It is estimated that the probability of a motorist being involved in a crash is 66 percent higher when an incident is already present. The potential for a secondary event increases when unaffected motorists slow down to observe what has happened. This gawking or rubbernecking contributes to driver distraction and subsequent crashes, congestion, and delay. Secondary incidents may also be caused by events such as vehicles overheating and becoming disabled while waiting for a primary incident to be cleared. This underscores the importance of developing HOV incident management plans that enable incidents to be dealt with safely and efficiently. Preventing civilians, tow-truck drivers, police officers, and other incident responders from being struck by passing vehicles should be the foremost objective.

Site management and traffic management duties are crucial safety-related activities undertaken by incident responders. Site management entails the organization and coordination of personnel and equipment at the scene of the incident to protect responders, victims, and motorists. Primary site management responsibilities are:

- Assessment of incident
- Prioritization of activities
- Notification of appropriate stakeholders
- Clear communications

Establishment of a formal incident command system allows responding agencies to coordinate their efforts without having to negotiate authority and develop response plans on scene or for each individual incident. Preplanned incident response strategies improve coordination and reduce response time and the potential for secondary events. On-site incident management activities should be complemented by the use of traffic management tools including lane closures, ramp metering, traffic signal adjustments, and designation of detours.

Incident Clearance

Incident clearance is an element of the overall incident management process that involves various activities:

- Removal of disabled vehicles, wreckage, and debris from the roadway
- Clearance of pedestrians and parked vehicles from the incident scene
- Return of the facility to normal operations

Due to the narrow lane width of contraflow facilities, stalled vehicles must either be pushed to the end of the lane or removed by tow truck. If towing is required, the tow vehicle must generally approach the disabled vehicle from the opposing direction. Drivers of emergency aid vehicles that may have to use this maneuver to reach vehicles in the contraflow lane should be adequately trained[8].

Severe incidents that result in infrastructure or equipment damage may require repair before the HOV facility can be safely reopened. General safety precautions used by operational personnel in the opening, closing, and reversal of HOV facilities should also be adhered to during the clearance of incidents. Police officers, firefighters, EMS personnel, and tow-truck drivers should receive proper safety training and equipment prior to responding to HOV-lane incidents. VMS signs and other methods of communication should be fully leveraged to promptly advise and update motorists regarding the location and status of the incident.

Enforcement

Enforcement is an essential component of HOV-lane operations. The presence of stationary and roving patrols on an HOV facility helps ensure that vehicle-occupancy and eligibility requirements are adhered to and that the lane operates as intended. Insufficient enforcement can result in higher violation rates, reduced travel-time savings, and decreased travel-time reliability for legitimate users. The potential safety implications of inadequate HOV-lane enforcement include congestion-related conflicts and crashes causes by excess demand and problems related to illegal maneuvers. Conversely, too much enforcement can also be detrimental to safety. Some facility operators report that the use of multiple officers at HOV-lane enforcement sites exacerbates gawking and congestion and creates congestion and additional safety concerns. Light, consistent enforcement appears to be an effective approach for reducing HOV violations and related safety incidents.

Occupancy Determination and Officer Safety

Among the safety issues associated with HOV-lane enforcement, preventing officer injury is the foremost consideration. Because an automated method of accurately determining the number of human beings in a moving vehicle has yet to be developed, officers must manually count the number of occupants in each vehicle. The following types of vehicles present particular challenges with respect to occupancy determination or verification:

- Panel vans
- Vehicles with tinted windows
- Vehicles carrying babies or small children
- Vehicles with children or adults lying down on a seat
- Vehicles with empty child seats
- Elevated pick-up trucks and sport-utility vehicles

Conditions such as darkness, sunlight glare and reflections, rain, fog, or snow can also complicate occupancy determination. The need for officers to position themselves at the roadside next to moving traffic creates a potentially dangerous enforcement environment. In order to reduce the exposure of officers to injury, vehicle speeds in active enforcement zones should be reduced through the use of variable message signs, beacons, or other traffic control devices.

Devices used to alert drivers to the presence of enforcement personnel on foot should be directed at HOV-lane traffic only. These warnings can be especially helpful in improving the safety of enforcement activities conducted during periods of darkness. Additional safety considerations regarding enforcement activities include:

- Use reflective vests to enhance the visibility of enforcement officers in low-light conditions.

- Avoid use of flashing police lights or other indiscriminant warning devices that distract drivers in adjacent lanes.

- Avoid use of enforcement beacons which tend to cause drivers to abruptly or illegally exit the HOV lane in an attempt to avoid enforcement.

- Enforcement vehicles should be parked in visible locations, outside of the lane of travel, and positioned so that they can protect officers from errant vehicles.

Data Collection

Data collection is an important component of HOV-lane operations. It enables facility operators and other stakeholders to gauge the success of the facility and identify weaknesses. Safety issues associated with the collection of HOV-lane data are similar to those encountered by enforcement personnel. Vehicle-occupancy data collection can be especially dangerous in freeway settings where speeds are high and the presence of data collectors may be unexpected. The following issues should be addressed to enhance the safety of data-collection initiatives:

- Authorization to collect data on an HOV lane should be obtained from the facility operator and local/state law enforcement authorities.

- Input from facility operators, enforcement personnel, transportation officials, consultants, researchers, or others that have undertaken similar efforts should be solicited to identify the safest and most convenient data-collection sites.

- Orientation and training sessions that include thorough reviews of data-collection sites, safety procedures and precautions, provision of safety vests and other equipment, and trial data-collection sessions should be mandatory prior to data-collection activities.

- Coordination of data-collection efforts with HOV-lane enforcement activities so that data collectors can take advantage of protected sites and slower traffic at enforcement locations.

- Collection of freeway vehicle-occupancy data from inside a marked vehicle such as a van to minimize the possibility of injury and to improve viewing vantage points.

- Position of data-collection vehicle should be safely outside of the lane of travel, in a clearly visible location.

CHAPTER THREE
SAFETY CONSIDERATIONS IN HOV-FACILITY PLANNING

Introduction

This chapter addresses safety considerations in the HOV-planning process. It begins with an overview of the relationship between HOV planning and safety and an explanation of regional, corridor, and facility-planning efforts. The identity and broad safety responsibilities of stakeholders engaged in HOV planning are subsequently presented. This is followed by an examination safety-related performance monitoring activities to be initiated during the HOV planning stage. The conclusion of the chapter highlights safety and planning aspects of the 2002 Puget Sound HOV Evaluation in Seattle, Washington. The planning and pre-design issues addressed in this chapter provide a context for the technical design and operational safety considerations presented in the following chapters.

Section headings in this chapter:

Overview of HOV Planning and Safety

The safety of HOV facilities begins at the planning stage, when initial decisions regarding the nature and scope of the project are made. Although safety is integral to the success of HOV projects, it has traditionally been addressed within the context of facility design and operations. The growth and evolution of HOV facilities and programming has focused increased attention on safety in the planning process. This section presents a concise review of this process and explains the relationship between HOV planning and safety.

Regional, Corridor, and Facility Planning

Planning for transportation improvements occurs at regional, corridor, and facility levels. Regional transportation planning often encompasses multiple jurisdictions and addresses the linkages among system elements. For example, a regional planning effort might be employed in a large urban area to support a network of HOV facilities that function efficiently as a unified system. Corridor planning is narrower and more specific in scope. It entails the identification of local transportation problems and the development and evaluation of alternatives for select corridors. Planning at this level is often motivated by safety and congestion concerns and may occur prior to or in the absence of a regional system-wide plan. The greatest degree of planning specificity occurs at the facility level. At this stage, the project type has been defined and pre-design and operational planning issues are examined.

The HOV planning process is embedded within this broader framework and typically takes years to complete. The extent of the planning process depends upon a number of factors, but is generally commensurate with project complexity. Large projects require a more detailed and refined approach to planning, while simplified planning practices may be acceptable for projects that are smaller or more limited in scope. Notwithstanding this flexibility, consideration of safety is essential.

Safety in HOV Planning

The purpose of addressing safety considerations in HOV planning is to raise their profile early in the project development process. This promotes approach results in the creation of HOV facilities that are inherently safer. The long-range benefits of this strategy include:

- Fewer inappropriate HOV-facility locations, types, designs, and operations
- Reduction in unsafe conditions on and around HOV facilities
- Prevention of HOV-facility incidents, crashes and related deaths, injuries, and property damage

The incorporation of safety considerations into the HOV planning process and its subsequent impact on HOV design and operations is illustrated in Figure 3-1.

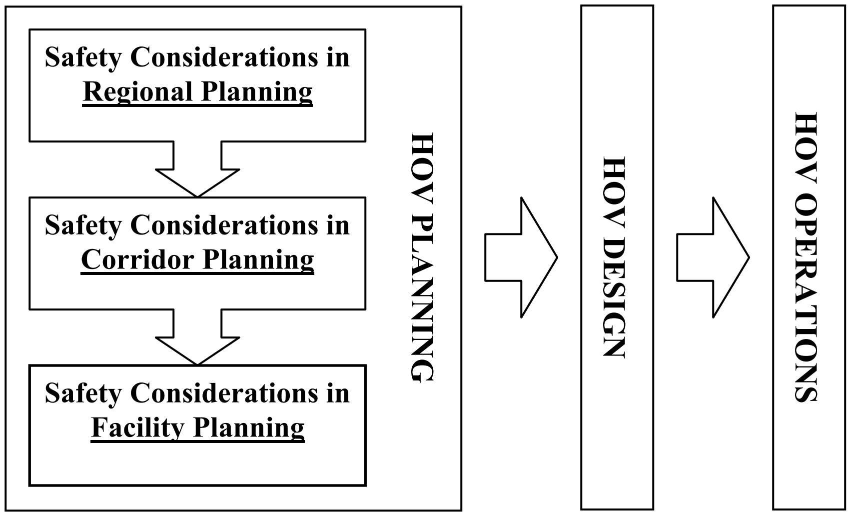


Figure 3-1. Development and Impact of Safety Considerations in HOV Planning.

Stakeholders with Safety-Related Planning Roles

Safety is an essential element in the HOV planning process. The identification and involvement of stakeholders in this process has implications for the ultimate safety of the HOV-facility design and operation. Project management teams, steering committees, and advisory groups are comprised of diverse entities to ensure that pertinent knowledge and perspectives are taken into account during project development. Integration of stakeholders begins at the earliest planning stages and continues through to facility-level planning.

The composition of HOV planning teams differs from project to project. A busway may require the participation and input of fewer entities than an arterial-street HOV facility. While the former is developed in a separate right-of-way and is usually restricted to transit vehicles, the latter may be implemented in highly congested environments distinguished by the interaction of multiple users, interest groups, and modes of transportation. Forming comprehensive planning teams for projects such as freeway and arterial-street HOV facilities can be especially challenging due to the array of safety issues they present. Potential conflicts among buses, passenger vehicles, bicyclists, pedestrians, and emergency and delivery vehicles create a variety of safety concerns that must be considered at the planning level.

The omission of relevant entities from the planning process creates input and knowledge gaps that can be detrimental to project safety and success. For example, failure to involve law enforcement agencies in HOV planning may result in a shortfall of enforcement resources or the selection of a corridor or facility type that is difficult or dangerous to enforce. This can promote high violation and crash rates,

By **engaging the proper stakeholders** in HOV-lane planning activities and emphasizing safety from the outset, safety problems can be minimized or avoided.

public opposition to the facility, and project failure. Similarly, insufficient involvement of local and state authorities in HOV planning efforts may result in a poor understanding of HOV-lane safety concerns among political leaders. Coordination and communication within a planning team is also critical to avoid confusion with respect to stakeholder responsibilities. The successful identification and involvement of entities in the HOV planning process requires linking project characteristics with the primary functions, expertise, and jurisdiction of stakeholders.

The following stakeholder descriptions highlight the principal entities that have safety-related responsibilities in HOV planning. It is important to note that the makeup of a planning team depends on specific project considerations and that the responsibilities of participant groups often overlap. Considerations such as roadway ownership and project type/characteristics normally dictate the lead agency for HOV planning and development efforts. Only groups whose planning activities are relevant to HOV safety are described below. Many of these entities are involved in design and operational aspects of the HOV lanes.

The State Department of Transportation is the agency that normally spearheads planning efforts for HOV facilities on freeways. It may also lead HOV projects developed on state-owned arterial streets. Engineers, planners, designers, operational employees, and traffic management personnel contribute to safety-related planning activities for these projects.

Transit Agencies are often in charge of planning for HOV projects such as busways that are developed in separate rights of way. Because these facilities are isolated and typically reserved for the exclusive use of buses, they are among the safest of all HOV facilities. Transit personnel, including bus drivers, transit HOV-lane police and courtesy patrols, and transit tow-truck drivers participate in safety-related planning efforts for freeway and arterial-street HOV facilities on which buses operate.

State and Local Police enforce HOV regulations and are responsible for responding to, investigating, and documenting crashes on and around HOV lanes. They also assist with HOV-lane incident management activities. Involvement of these stakeholders in the planning process is crucial. Law enforcement officers are exposed to the day-to-day operations of the facility and bring valuable practical knowledge and insight to the HOV planning process.

The State Department of Public Safety (DPS) or Department of Motor Vehicles (DMV) is the agency that usually compiles and codes crash information into database format so that it can be analyzed, queried, and disseminated. This information is based on crash reports prepared by state or local law enforcement and safety personnel.

County and City Departments may lead planning efforts for arterial-street HOV lanes and assist with safety issues related to queue bypasses and local infrastructure connections to busways and freeway HOV facilities.

Metropolitan Planning Organizations are usually engaged in large HOV-lane planning initiatives that affect multiple jurisdictions within a region. They often play a coordinating role in these projects, collaborating with local, state, and federal entities. MPOs can exert influence over HOV-lane safety and development through policies that govern acceptable facility types and methods of provision.

Consultants and Contractors may be involved in the planning process for virtually any type of HOV facility. Planners, designers, researchers, and others employed by these entities assist project stakeholders in the identification of candidate corridors and facility types, collection of data, analysis of project options and facility designs, and other safety-related planning tasks. These stakeholders may also be hired to conduct safety evaluations of existing or proposed HOV facilities.

Toll Authorities are engaged in the HOV planning process if they are considering priority lane treatments or queue bypasses on their facilities. Toll Authority personnel typically collaborate with HOV planning stakeholders at the state and local levels to address safety considerations associated with these treatments.

Emergency Services provided by entities such as the fire department, police, emergency medical services, and tow-truck operators may utilize HOV facilities to respond to incidents and crashes on the HOV lane or elsewhere. The unique objectives of these entities and the operational characteristics of their vehicles have implications for HOV safety planning.

Public Groups such as transit riders and commuters must be included in the HOV planning process if it is to be successful. These groups ensure that safety issues and perspectives of concern to the public are considered by the project management team. Public participation in HOV planning efforts is also important from an information, awareness and educational perspective and is essential for safety-related planning initiatives such as focus groups, forums, and surveys.

Additional Stakeholders such as rideshare agencies, bicyclists, neighborhood associations, businesses, schools, hospitals, and other entities also have a stake in the HOV planning process. Like public groups, these stakeholders contribute to HOV safety by raising issues of relevance to their constituents and providing input regarding facility planning and development.

Table 3-1 provides a summary of the safety-related activities of HOV planning stakeholders.

Table 3-1. Safety-Related Stakeholders and Activities in HOV-Lane Planning.

Stakeholder	Safety-Related Activity
State Department of Transportation	• Corridor and facility analysis/selection • Planning for incident management • Data collection/performance monitoring
Transit Agency	• Corridor and facility analysis/selection • Planning for bus operations • Possible enforcement site selection, planning • Planning for incident management • Data collection/performance monitoring
State and Local Police	• Enforcement site selection and planning • Planning for incident management • Prepare crash reports
The State Department of Public Safety or Department of Motor Vehicles	• Compilation of crash information
Counties and Cities	• Corridor and facility analysis/selection • Data collection/performance monitoring
Metropolitan Planning Organization	• Corridor and facility analysis/selection
Consultants and Contractors	• Corridor and facility analysis/selection • Data collection/performance monitoring
Toll Authorities	• Treatment analysis/selection
Public Groups	• Corridor and facility analysis/selection • Provide stakeholder information/input
Emergency Services	• Provide stakeholder information/input
Other stakeholders including Rideshare Agencies, Emergency Medical Services, bicyclists, tow-truck operators, neighborhood associations, businesses, hospitals, others	• Corridor and facility analysis/selection • Provide stakeholder information/input

Safety Considerations in the Development of HOV-Lane Performance Monitoring Programs

Consideration of safety and the development of HOV-lane performance monitoring programs should begin prior to design of an HOV facility. This section explains the role and importance of safety considerations in this element of HOV planning process.

Initiate a Performance Monitoring Program

Performance monitoring programs are implemented to determine whether HOV projects are achieving safety and other objectives. They also provide valuable information about the underlying reasons for facility performance. The collection and analysis of safety-related information enables stakeholders to make appropriate adjustments to project design, operations, and management. Effective HOV performance-monitoring activities entail the collection of detailed safety information on general-purpose lanes in the proposed HOV-lane corridor during the planning phase. A common obstacle to HOV-lane safety assessment and improvement is the scarcity of valid crash data collected prior to HOV implementation. Comparisons of before-and-after crash data sets allow practitioners to go beyond qualitative observations in analyzing the safety impact of HOV treatments. A description of HOV-lane safety evaluation is included in Chapter 5 of the handbook.

Evaluation of HOV Lane Performance

Collection of baseline safety data during planning process helps to assess current conditions and establishes a “before” situation on which HOV performance can be compared to after implementation.

Collection of baseline safety data on general-purpose lanes should be undertaken years prior to the start of HOV-lane construction in a corridor. This underscores the need to establish a performance monitoring program as early as possible in the HOV planning phase. The following information focuses on the safety aspects of HOV performance monitoring activities. The Federal Highway Administration’s (FHWA) *HOV Performance Monitoring, Evaluation and Reporting Handbook* provides additional information on these programs.

The main steps involved in developing and conducting an HOV performance monitoring program are shown in Figure 3-2. An explanation of the role of safety in each of these steps is provided below.

Identify Safety Goals and Objectives
↓
Identify Safety Measures of Effectiveness
↓
Identify Safety Data Requirements
↓
Collect Safety Data
↓
Analyze Safety Data
↓
Report Safety Results – Modify Operations As Needed

Figure 3-2. Steps in Developing and Conducting an HOV Performance Monitoring Program[3].

Identify Safety Goals and Objectives

Identification of safety-related goals and objectives is the first step in HOV performance monitoring. Safety goals are general project intentions expressed as succinct statements that emphasize safety issues, among other project considerations. These goals serve to identify safety as a project priority and advance safety issues throughout HOV development. An example of a safety goal for an HOV facility might be:

- Develop and implement an HOV facility that provides a safe transportation option.

At the corridor and facility-planning levels, project stakeholders refine the safety goal(s) into more detailed and targeted objectives. Objectives define a desired result and may include specific actions and time frames. The following objectives could be developed for the abovementioned safety goal:

- Implement the HOV lane within five years without increasing crash rates on adjacent general-purpose lanes.
- Maintain HOV-lane crash rates at a level equivalent to or lower than adjacent general-purpose lanes.

A number of considerations should be taken into account when developing HOV safety goals and objectives. While the goals themselves may be broad, associated objectives should be well-defined, meaningful, and measurable. Goals and objectives should be realistic, consistent with safety plans and visions of oversight agencies, and be agreed upon by all planning stakeholders. This strengthens support for project safety and helps sustain focus on related considerations as the project is carried forward into design and operation. Prioritization of safety objectives may be necessary to ensure that available resources are properly allocated. Finally, it is desirable to establish time frames for achieving safety objectives. The effect of HOV-lane construction and motorists' adjustments to new HOV facilities may temporarily skew crash statistics. The collection of several years of before-and-after safety information is thus required to undertake a valid trend analysis.

Identify Safety Measures of Effectiveness

Measures of effectiveness provide a means for undertaking quantitative safety analysis and assessing whether safety objectives have been met. Each objective may have one or more corresponding measure of effectiveness (MOE). These measures should be precise and focus on the core elements of their respective objectives. Examples of MOEs that correspond to the safety objectives listed above are:

- Number, type, severity, and location of crashes for the HOV lane and each adjacent general-purpose lane
- Crash rates per million vehicle-kilometers (or miles) traveled on the HOV lane and each adjacent general-purpose lane
- Crash rates per million passenger-kilometers (or miles) traveled on the HOV lane and each adjacent general-purpose lane

Identify Safety Data Requirements

Identification of safety data needs flows directly from the previous step. Data requirements for each MOE should be unambiguous, and the method of collecting and analyzing the data should be clear. For example, determination of crash characteristics on HOV and general-purpose lanes requires access to detailed law-enforcement crash records. In order to ascertain crash rates per million vehicle-kilometers (or miles) of travel, precise information on traffic volumes is needed. Calculation of crash rates per million passenger-kilometers (or miles) of travel entails manual collection of vehicle-occupancy data. This information must be gathered regularly and reported in an accurate and standardized fashion so that credible analyses and comparisons can be made.

Collect Safety Data

Baseline safety data must be collected for two or three years in advance of HOV-lane construction to permit meaningful before-and-after comparisons. The collection of safety data should begin in the project planning phase, be maintained throughout HOV-lane design and construction, and continue on an ongoing basis once the facility is operational. Before-and-after crash data analysis and comparison are jeopardized by insufficient collection of "before" data, as this information is difficult to accurately recreate. Diverse techniques are employed in the collection of safety data, including:

- Manual observation/counts of vehicle type and occupancy levels (used to account for impact of vehicle type on crash rates, and calculation of crash/injury rates per passenger-kilometers of travel)

- Electronic collection of traffic volume information using loop detectors, automatic vehicle identification systems, electronic toll collection technology, and other means

- Review of electronic and hard-copy crash data and reports prepared and coded by law enforcement and motor vehicle safety agencies

There are numerous challenges associated with the collection and use of safety-related data in HOV planning. First, manual collection of safety data can be dangerous. This is especially true in freeway settings where vehicle speeds are high and the presence of data collectors may be unexpected. Because an automated method of accurately determining the number of human beings in a moving vehicle has yet to be developed, manual collection of this information is required. Data-collection authorization from local and state law enforcement authorities and transportation officials should be secured before proceeding with a manual data-collection effort. The input of consultants, researchers, or other local entities that have undertaken similar efforts should also be solicited to identify safe and appropriate data-collection sites and procedures.

Other safety information is collected by law enforcement and safety personnel during the preparation of crash reports in the field. These reports are expensive and time consuming to prepare and process. Moreover, they often contain detailed information and sketches that are not electronically coded and must be reviewed in hard-copy format for safety analysis purposes. Figure 3-3 shows a diagram contained in a crash investigator's report of an HOV-lane collision. In order to reduce the cost and maximize the utility of data, information should be gathered simultaneously where possible. For example, vehicle-occupancy data-collection efforts generate passenger, vehicle classification, and traffic volume information that can be used for safety assessments and a variety of other purposes. Standardized procedures and techniques should be used by data-collection and analysis personnel involved in before-and-after data-collection efforts so that data integrity and the validity of comparisons are maintained.

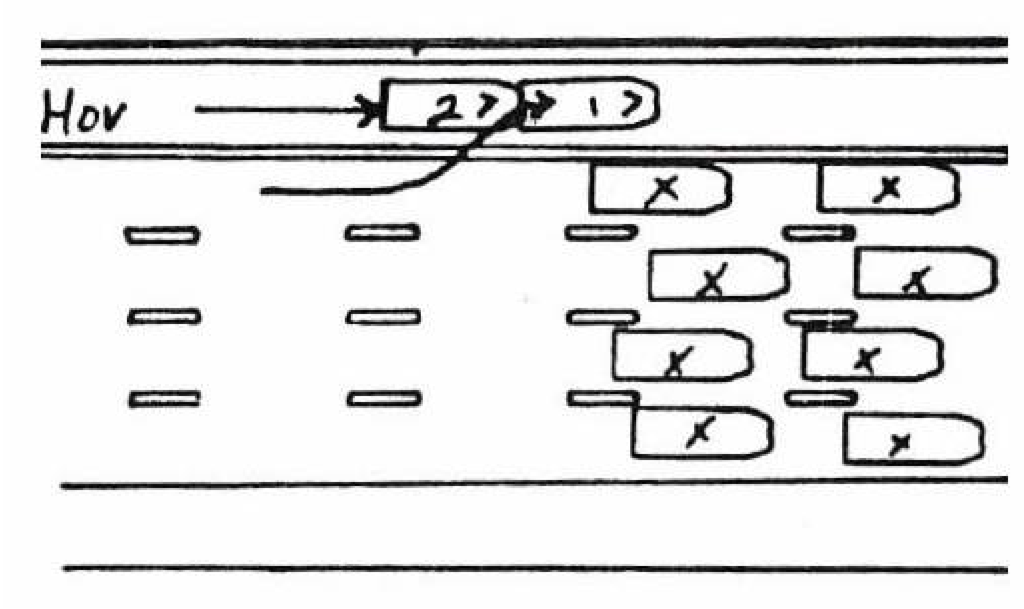


Figure 3-3. Example of Crash Investigator's Sketch of an HOV-lane Collision[10].

Issues concerning the quality and reliability of crash information can negatively impact HOV safety planning efforts. Problems such as coding errors, underreporting of crashes, incorrect assessment of variables, erroneous or insufficient crash location information, and lack of data uniformity can preclude effective HOV performance monitoring. Developing safe, appropriate, and financially viable data-collection techniques is a key safety-related planning requirement. The importance of understanding and addressing concerns associated with crash data is discussed further in the Future Research section (Chapter 7) of this handbook.

Developing safe, appropriate, and financially viable **data-collection techniques** is a key safety-related planning requirement.

The remaining steps in the performance monitoring process, *Analysis of Safety Data* and *Reporting Safety Results*, occur after the HOV lane has been planned, designed, and implemented, and data on its safety performance collected and analyzed. These safety evaluation considerations affect facility operations and are addressed in the Operations section (Chapter 5) of the handbook.

HOV Safety Planning: Puget Sound HOV Evaluation

Name – Puget Sound HOV Evaluation

Safety Relevance – Evaluation incorporates safety-related planning, analysis, and design practices/considerations in the assessment and conversion of full-time HOV lanes to part-time HOV lanes

Contact – Mark Hallenbeck, Washington State Transportation Center (TRAC), Tel. (206) 543-6261, http://www.wsdot.wa.gov/HOV/pugetsoundeval/default.htm

Location – Seattle, Washington	**Facility Type(s) –** Concurrent buffer-separated HOV lanes
Safety Objective(s) – Determine feasibility and potential safety impacts of changing HOV hours of operation, apply crash mitigation techniques	**Project Date(s) –** Evaluation conducted in 2002, mitigation techniques implemented and lanes converted in 2003, post-implementation evaluation ongoing

Description

The Washington State Department of Transportation (WSDOT) evaluated the operation of several freeway HOV lanes in the Puget Sound region to determine if the effectiveness and efficiency of the highway system could be enhanced by opening them to non-HOV traffic during nights and weekends. Among the issues evaluated was the safety impact of changing occupancy restrictions for the facilities from 24 hours per day, seven days per week to weekdays only. Analysis concluded that allowing general-purpose vehicles to use the HOV lanes during nights and weekends was operationally feasible and safe provided certain facility upgrades were undertaken. These improvements were intended to enhance safety during both the HOV and non-HOV periods. The total cost of implementing the safety improvements and converting the HOV lanes to part-time operation was approximately $2 million. The FHWA authorized conversion of the lanes and provided safety guidance and assistance to WSDOT in the planning and design process.

Safety Considerations

A number of safety issues were considered in the Puget Sound HOV Evaluation. Collection of historical and current information on traffic volumes and crash rates permitted detailed analyses of the potential safety impact of the proposed changes. Crash forecasts were developed, and merging and run-off-the-road collisions were modeled. These considerations played an important role in feasibility assessments, planning, and the safe design of the converted HOV lanes. An analysis of merging crashes revealed that opening the HOV lanes to general-purpose traffic at night and on weekends would have a negligible safety impact so long as the direct access ramps remained restricted to HOV traffic. However, growth in HOV-lane traffic was projected to raise the probability of run-off-the-road crashes. To address this concern, mitigation techniques were identified and implemented before general-purpose traffic was permitted on the lanes. These included installation of shoulder rumble strips, improved striping, raised profile edge lines, additional guardrails and median barriers, and improved signage.

CHAPTER FOUR
SAFETY CONSIDERATIONS IN HOV-FACILITY DESIGN

Introduction

This chapter provides an analysis of safety considerations in HOV facility design. Relevant stakeholders are identified and safety considerations pertaining to different types of HOV facilities are addressed. Geometric design standards prescribed in the American Association of State Highway and Transportation Officials *Guide for High-Occupancy Vehicle Facilities* are reviewed and potential safety implications are explained. This information is supplemented by safety considerations and guidance distilled from published HOV-lane crash studies and reports and information made available by practitioners. Safety tradeoffs and compensatory measures that have been borne out through operator experience and research are also presented. The case study at the conclusion of the chapter describes a vehicle arresting barrier used to prevent wrong-way movements and collisions on a Dallas-area reversible HOV lane. The design-related safety considerations addressed in this chapter build on the safety planning information presented in Chapter 3 and offer a view to related operational issues that are dealt with in Chapter 5.

Section headings in this chapter:

Stakeholders with Safety-Related Design Roles

Design of an HOV facility is a specialized activity that may involve fewer stakeholders than the planning effort. A subgroup of the project development or management team comprised of design personnel from relevant entities is usually formed to lead the design process. Input from other stakeholder groups that will use or be affected by the HOV lane is also incorporated into this process. As in the planning stage, the involvement and roles of stakeholders vary according to project type and location, and responsibilities frequently overlap. The agencies and groups presented below influence HOV-lane safety through the evaluation and selection of key facility design elements.

<u>The State Department of Transportation</u> is usually the lead agency for designing HOV facilities on freeways and state-owned arterial streets. State engineers, planners, and designers may collaborate with contractors and personnel from other

agencies. They may also participate in the design of busways and HOV facilities in separate rights-of-way.

Transit Agencies are often in charge of designing HOV projects such as busways that serve transit operations. In addition, transit-agency personnel may be involved in designing freeway and arterial-street HOV facilities on which buses operate. This helps ensure that unique safety issues associated with bus operations are considered in the design of these facilities.

State and Local Police play an important role in the design of all types of HOV facilities. Personnel from state, city, county, and transit police departments provide critical input on enforcement design treatments.

County and City Departments may head the design team for arterial-street HOV lanes and assist with design issues related to queue bypasses and local infrastructure connections to busways and freeway HOV facilities.

Metropolitan Planning Organizations often support state DOT personnel in the design of freeway HOV facilities. Some MPOs have established guidelines that regulate candidate HOV-lane types and facility designs.

Emergency Services provided by entities such as fire departments, emergency medical services, and tow-truck operators may depend on HOV facilities to respond to incidents. The unique objectives of these entities and the operational characteristics of the vehicles they use can entail special safety considerations in facility design.

Federal Agencies such as the Federal Highway Administration and the Federal Transit Administration (FTA) sponsor HOV projects and can influence facility safety through the approval or rejection of a facility design or design exception. FHWA and FTA employees frequently provide technical assistance to state and local personnel spearheading HOV-lane design efforts.

Additional Stakeholders such as carpoolers, bicyclists, neighborhood associations, hospitals, schools, and businesses should also be consulted during the HOV-lane design phase to ensure that facility features safely accommodate intended uses.

Table 4-1 provides a summary of safety-related design roles for each of the abovementioned stakeholders.

Table 4-1. Safety-Related Roles of Stakeholders Involved in HOV-Facility Design.

Stakeholder	Safety-Related Activity
State Department of Transportation	• Design/assist with design of facility
Transit Agency	• Design/assist with design of facility
State and Local Police	• Assist with design of enforcement elements
Counties and Cities	• Design/assist with design of facility
Metropolitan Planning Organization	• Assist with design of facility
Emergency Services – EMS, Fire Department, tow-truck operators	• Identify stakeholder needs and provide input for facility design
Federal Agencies – FHWA and FTA	• Provide technical assistance, approve/reject facility design
Other stakeholders including carpoolers, bicyclists, neighborhood associations, businesses, hospitals, schools and others.	• Identify stakeholder needs and provide input for facility design

Safety Considerations in HOV-Facility Design

The process of designing an HOV facility flows from the planning phase in which a specific facility type is proposed. Safety-related design issues encompass:

- Lane and shoulder widths
- Provision and design of buffers
- Delineation and separation techniques
- Access treatments and signage
- Enforcement-sites location and design

The information in this section addresses these and related considerations from a safety perspective. Guidance provided is based on the best available information regarding the relationship between HOV facility design and safety. Geometric design values and cross-sectional diagrams used in this chapter have been excerpted from the most up-to-date HOV design guidelines published in the AASHTO 2004 *Guide for High Occupancy (HOV) Facilities*[6]. The reader is encouraged to consult this and other sources such as the *Manual on Uniform Traffic Control Devices* for additional details on HOV-facility cross sections and design. Desirable and minimum cross-section information is presented here as general guidance. Minimum design values should only be considered where project constraints preclude adoption of the desirable design and all comparable alternatives.

The development of HOV lanes, like all roadways, entails consideration of a variety of design criteria. These are not limited to the HOV lane itself, but include the drivers and vehicles that will use the facility and the context in which the project will be developed. HOV lanes may be open to a wide range of transportation modes, including regular or articulated buses, ambulances, tow-trucks, vans, light trucks, cars, motorcycles, and bicycles. Appropriate vehicles must be considered in the facility design process to ensure that the safety performance of the facility is not compromised. For example, buses are often used to determine curve and intersection radii of an HOV lane. Stopping sight distance is typically based on a driver of a small vehicle such as a passenger car that is closer to the surface of the roadway[16]. In reviewing the facility design elements that follow, it is important to bear in mind that overall HOV-lane safety is dependent on a variety of issues, some of which go beyond the considerations examined.

Designing for Safe HOV Lane Access

To minimize vehicle conflict on and around facilities, designers of access treatments should consider:

- Applying the same geometric criteria as would be used for a freeway ramp, including locally recognized entrance and exit standards.
- Strategically positioning designated outlets so as to prevent significant weaving conflicts across freeway lanes in instances involving at-grade access with the adjacent freeway lanes.
- Avoiding HOV lane drops. The ideal exit terminal treatment is a continuous lane.

Performing a weave analysis to ensure that existing and projected traffic volumes can be safely accommodated by the selected access design.

General Access Considerations

Ingress and egress treatments are the design features that enable vehicles to enter and exit an HOV lane. They are fundamental to the design of an HOV lane and can have a profound effect on vehicle conflicts occurring on and around the facility. The following points highlight general safety-related considerations pertaining to HOV ingress and egress design (adapted from[6, 7, 8]

- Where possible, the same geometric criteria should be applied as would be used for a freeway ramp, including locally recognized entrance and exit standards. HOV-lane ramps should be designed to the acceleration and deceleration characteristics of loaded buses. Extremely long, gradual tapers should be avoided on exit ramps, as motorists may inadvertently follow the taper assuming it is the main roadway.

- Sight distance is particularly critical due to the proximity of barriers to ramp-lane alignments. Lateral clearances are often no greater than 0.6 m (2 ft) from the edge of the travel lane to the barrier. Where practical, removal of barrier-mounted glare screens that reduce sight distance or slight adjustments in striping alignment may be necessary within the ramp envelope to accommodate the proper design speed.

- The location of ingress/egress facilities is influenced by a number of factors. For example, direct access ramps to/from local streets should be made with candidate streets that currently do not have freeway access, so as to better distribute demand and prevent overloading existing intersections. For at-grade access with the adjacent freeway lanes, designated outlets should be strategically positioned so as to prevent significant weaving conflicts across freeway lanes.

- A freeway lane should not turn into an HOV-lane; the HOV lane should be located out of the normal path of travel. Motorists desiring ingress to the HOV facility from a freeway lane should be required to make an overt maneuver. Similarly, intermediate HOV off-ramps should be designed so that an overt maneuver is required to exit the facility and HOV through traffic is not inadvertently exited.

- HOV-lane access ramps should provide adequate space for possible metering and storage.

- Single HOV lanes do not allow for passing or lane changes within the facility. Left- or right-hand exits from a single-lane HOV lane are equally valid and equally safe. The standard "right-hand only" rule for entrance and exit ramps should not apply for HOV lanes.

- During initial operations of new HOV facilities, demand may not warrant direct or elevated ramps. If demand subsequently increases, a retrofit design could be difficult, expensive, and require safety compromises during construction. When exclusive ramps are not included in the initial project design, provisions should be made so that the ramps can be safely added later.

- Safety lighting should be applied for all ingress/egress locations using the same warrants applied for urban freeway entrance and exit ramps.

- HOV lane drops should be avoided. Where HOV lanes are terminated by dropping either the HOV lane or a general lane, a forced merge is created. This is a hazardous condition, particularly at locations having high speed differential between the HOV lane and general travel lanes. The ideal exit terminal treatment is a continuous lane. If any lane must be dropped at the end of an HOV facility, it is preferable to drop a right lane at a high exit demand location and shift all lanes to the left.

- Weave analysis should be performed to ensure that existing and projected traffic volumes can be safely accommodated by the selected access design.

General Signage Considerations

HOV-lane signage, together with pavement markings and other traffic control devices, performs an important safety function by providing travelers with

Designing for Driver Information

To minimize vehicle conflict on and around facilities, designers of signing and pavement markings in HOV lanes should consider

- Guidance provided by the MUTCD for signing and pavement markings for HOV facilities.
- Consistency in placing signs at a distance that allows drivers ample time to react, regardless of type (overhead or side-mounted). Whenever possible, mount the HOV sign directly over the affected lane.

information that is necessary for safe use of the facility. Consistent and frequent signage is required prior to and on HOV lanes due to the relatively large amount of information that must be conveyed to motorists. Common signage problems that can contribute to motorist confusion and HOV-lane safety issues include inconsistent signage, signage that does not adhere to MUTCD standards, and poor signage location or positioning. These problems are most prevalent where signage or geometric inconsistencies occur within a region or HOV-lane network. HOV-lane signage must be clear and succinct. The general guidelines below should be observed to minimize or prevent signage-related confusion, erratic maneuvers, and other safety issues from developing on HOV facilities (adapted from[9]):

- Adequate advance signage should be provided and pavement markings should be used to emphasize lane designation.
- Make regulatory signs the standard MUTCD white diamond symbol over a black background in the upper left-hand corner and black lettering on a white background for the rest of the sign. Follow standard MUTCD guidelines for color, font, and type size so that signs are easily identified and read and are not lost in clutter.
- Make guide signs the standard MUTCD white lettering on a green background.
- Make the sign size consistent with the speed of the traffic reading it.
- Ensure information is presented consistently: identify the lane (top line), who it applies to (second line), and applicable time of day and day of week (last line).
- Be consistent about where signs are placed (overhead or side-mounted) and at a distance that gives drivers ample time to react. Whenever possible, mount the HOV sign directly over the affected lane.
- When conveying a lot of information, use concisely worded signs, not symbols.
- Use the diamond symbol to mark the pavement on all HOV lanes, and repaint symbols as needed.
- Use a standard signing strategy.

General Enforcement Considerations

Enforcement is an important component of HOV-lane design and operations and can have a significant impact on the success and viability of an HOV project. The enforcement-related design considerations addressed here focus specifically on safety. The term "enforcement area" is used to refer to a number of potential design treatments that provide space for police personnel to monitor an HOV facility, to pursue a violator, and to apprehend a violator and issue a ticket or a citation[6]. Depending on the type of facility in question, certain design considerations must be taken into account to protect the safety of enforcement officers, facility users, and general-purpose traffic. If these considerations are not properly accounted for in the design process, facility safety issues may arise, contributing to enforcement problems and project failure. These considerations, detailed in the facility subsections of this chapter, include:

- Consultation with enforcement personnel and agencies in the facility design process
- Additional lighting, signage, traffic control devices, and provision of safe observer vantage points
- Minimum enforcement area width of 3.6 to 4.3 m (12 to 14 ft)
- Minimum enforcement area length of 30 m (100 ft) (dependent on facility type, traffic speeds, violation rates, and violator storage requirements)

Designing for Safe Enforcement Operations

To avoid facility safety issues once in operation, consultation with enforcement personnel and agencies should occur during the facility design process. Items to consider include additional lighting, signage, traffic control devices, and provision of safe observer vantage points.

Table 4-2 highlights key enforcement attributes associated with different types of HOV lanes.

Table 4-2. Example Enforcement Attributes Associated with Different Types of HOV Facilities[6].

Type of HOV Lane	Preferred Enforcement Attributes	Minimum Enforcement Attributes
Barrier-Separated (Two-way and Reversible)	• Enforcement areas at entrances exits	• Enforcement areas at entrances or exits
Concurrent Flow	• Continuous enforcement shoulders with periodic barrier offsets • Continuous right-side shoulders	• Periodic mainline enforcement areas • Monitoring areas • Continuous right-side shoulders
Contraflow	• Enforcement area at entrance • Continuous shoulder for enforcement	• Enforcement area at entrance
Queue Bypass	• Enforcement area on right-side shoulder • Continuous right-side shoulder • Duplicate signal head facing enforcement area at ramp meters	• Enforcement monitoring pad with continuous right-side shoulder downstream

Geometric Design Considerations

Geometric Design for Safe HOV Facilities

The *AASHTO Guide for the Design of High-Occupancy Vehicle Facilities* provides the most comprehensive design guidance for ensuring safe HOV facilities. It is a peer-reviewed document based on decades of HOV experience.

Geometric design standards for HOV-lane cross sections, access treatments and enforcement sites help ensure that the basic safety of the facility is not compromised in the design process. Analysis of safety considerations associated with these standards (and variations on them) provides guidance regarding the effect of design decisions on HOV-lane safety performance. Recommended AASHTO designs for the most prominent types of HOV facilities are provided in the sections that follow and supplemented with safety and design-related operator experience. This information has been developed through decades of HOV operations. The facility types described are categorized as barrier-separated and non-barrier separated facilities, given the nature and similarity of safety concerns associated with these broad categories:

- Barrier-separated facilities
  - HOV lanes in separate rights of way
  - Reversible and two-way barrier-separated HOV lanes
  - Contraflow HOV lanes
- Non barrier-separated facilities
  - Concurrent buffer-separated and non-separated HOV lanes
  - Arterial street HOV lanes
  - Queue bypass HOV lanes

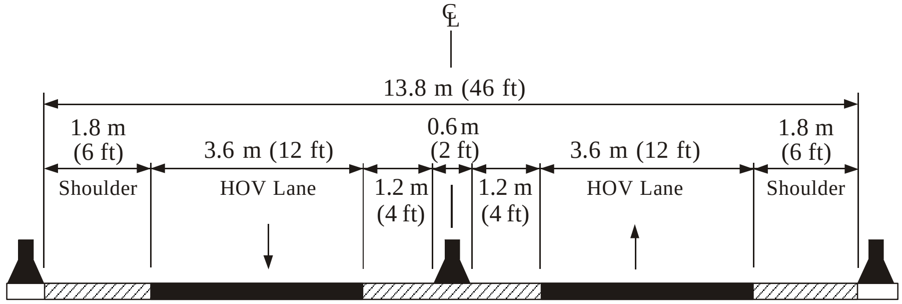
Barrier-Separated HOV Facilities

The sections below describe the design elements for the different types of barrier-separated HOV facilities, followed by a discussion of safety-related issues associated with barrier-separated lanes based on research and operator experience.

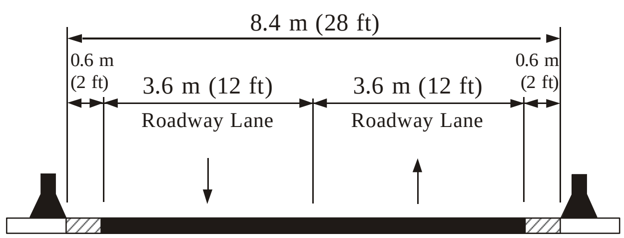
HOV Lanes in Separate Rights of Way

Facility Cross Section

Freeway HOV lanes in separate rights-of-way are physically isolated from general-purpose lanes. They are typically designed for the exclusive use of buses; operate as two-lane, two-directional facilities; and present relatively few safety issues. As illustrated in Figure 4-1, the design envelope required for safe operation of this facility type varies from 13.8 m (46 ft) to a minimum of 8.4 m (28 ft).



DESIRABLE[1]



MINIMUM[2] (BUS ONLY, LOW SPEED AND LOW VOLUME)

[1] HOV envelopes in one direction over 6.6 m (22 ft) may invite passing if HOV lane is not restricted to bus-only (i.e., professional driver) operations. Enforcement of the facility can be performed at the ends and access locations if the facility is not restricted to bus only.

[2] Operational treatments should be incorporated if the minimum design cross section is used. The minimum cross section should only be used over corridors with constrained right-of-way width for bus-only (i.e., professional driver) operations at low speed and low volume.

Figure 4-1. Examples of Cross Section for Busway or HOV Lane in Separate Right-of-way[6].

A concrete median barrier is recommended for separating opposing traffic flows on facilities that are open to carpools and vanpools. The desirable cross section includes travel-lane widths of 3.6 m (12 ft), shoulder widths of 1.8 m (6 ft), and lateral clearances of 1.2 m (4 ft) to the median barrier[6]. This cross section enables vehicles traveling at low speeds to pass a disabled bus. For additional vehicle and pedestrian safety, a passing lane at online transit stops should be incorporated into the design.

Virtually all U.S. HOV lanes in separate rights-of-way serve buses only and have been designed with a median consisting of a solid double yellow line. This and other minimum design features such as lateral clearances of 0.6 m (2 ft) to barriers should only be considered on exclusive busways that are characterized by low-speed, low-volume operations. The use of minimum design standards on facilities open to a diverse vehicle mix operating at higher speeds may result in unsafe conditions. A general summary of the cross-section guidelines for HOV lanes in separate rights-of-way is provided in Table 4-3.

Table 4-3. Summary of Cross-Section Guidelines for HOV Lanes in Separate Rights of Way.

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	13.8 m (46 ft)	8.4 m (28 ft)
Lane Width	3.6 m (12 ft) per lane	3.6 m (12 ft) per lane
Shoulder/Buffer Width (Right, Left)	1.8 m (6 ft), 1.2 m (4 ft) per direction	0.6 m (2 ft), 0.6 m (2 ft)
Internal Lane Separation	0.6 m (2 ft) median barrier	None (low-speed, low-volume busway)

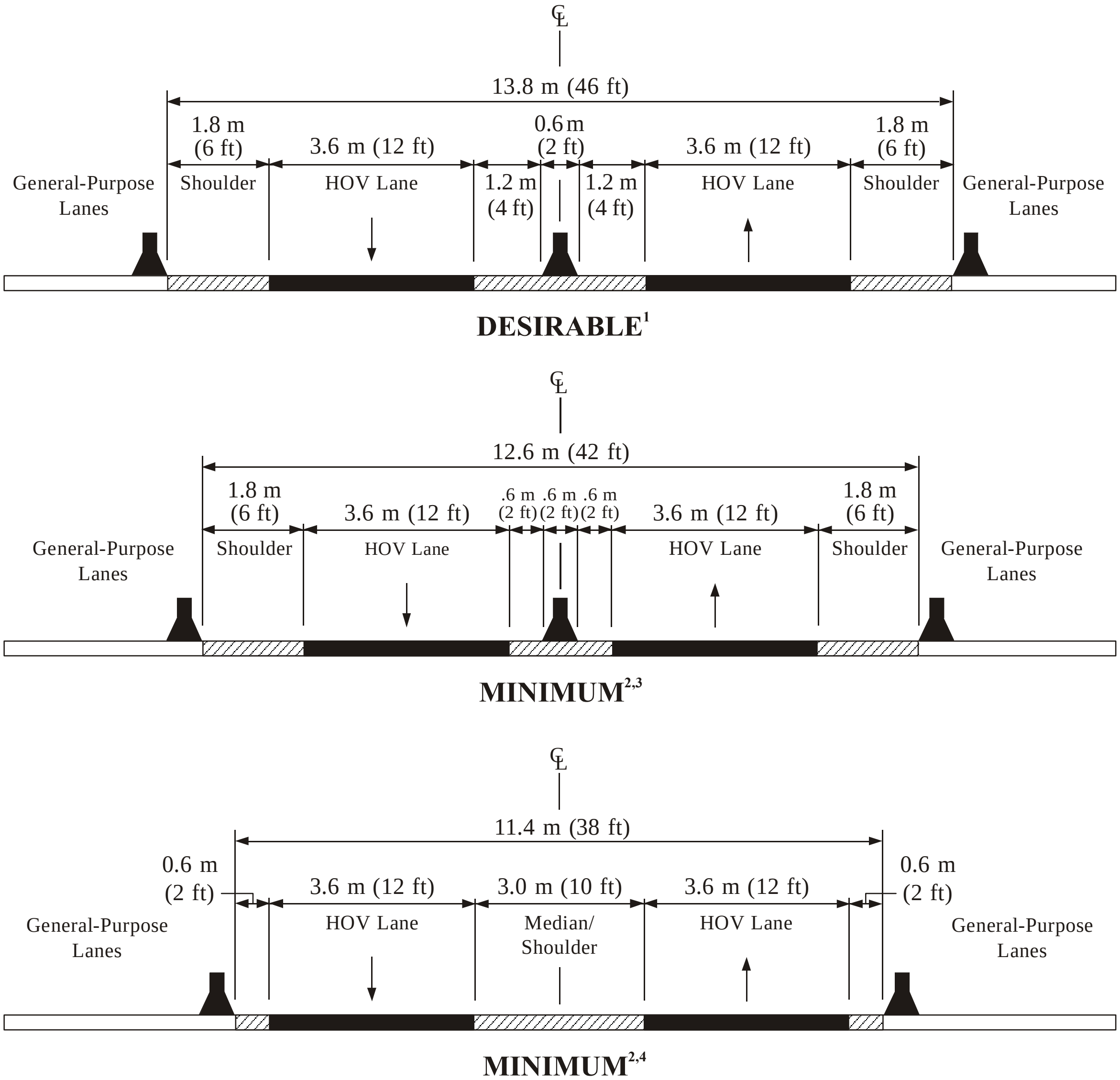
Access and Enforcement Treatments

HOV lanes in separate rights-of-way usually offer a limited number of access points to and from park-and-ride lots and local streets. Access locations should incorporate restrictive traffic control devices such as gates, barricades, flashing beacons, and no-entry signs (as appropriate) to prevent wrong-way movements[8]. The number and severity of barrier-end collisions at access points can be attenuated through the use of highly-visible crash cushions. Ingress points should be clearly signed with respect to vehicle eligibility and hours-of-operation regulations to prevent illegal or unsafe entry. Ineligible vehicles such as cars and vans are easily spotted on exclusive busways. Transit drivers are therefore generally relied upon to report violators, who can then be intercepted at facility egress points.

Two-Way Barrier-Separated HOV Lanes

Facility Cross Section

Two-way barrier-separated HOV lanes are located within the freeway right of way, permit simultaneous travel in both directions, and are physically separated from the general-purpose lanes by concrete barriers. As shown in Figure 4-2, the desirable design envelope for safe operations of this type of facility is 13.8 m (46 ft). Minimum facility width is 11.4 m (38 ft). Both minimum and desirable designs include standard lane widths of 3.6 m (12 ft).



[1] HOV envelopes in one direction over 6.6 m (22 ft) may invite passing. A full breakdown shoulder is not provided although vehicles can still maneuver around disabled vehicles. Enforcement of this facility is performed at the ends and access locations.

[2] Operational treatments should be incorporated if the minimum design cross sections are used. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility.

[3] The width of this cross section provides the minimum space required for a bus to pass a disabled bus at slow speed.

[4] Shared median minimum cross section should only be used for two-way ramps, short connector section, low-volume HOV lanes, or other lower speed facilities.

Figure 4-2. Examples of Cross Sections for Two-Way Barrier-Separated HOV Facilities[6].

A concrete median barrier should be incorporated into the design if the facility is intended to accommodate carpools and vanpools operating at high speeds. This prevents head-on collisions if a vehicle loses control in the lane. Minimum lateral clearance of 0.6 m (2 ft) to the median barrier is required to reduce inadvertent vehicle-barrier contact, and an offset of 1.2 m (4 ft) desirable for increased safety. Decisions regarding the precise lateral offset should be coordinated with other safety-related design considerations such as sight distances, design speed, and signage. Where the use of a median barrier is not feasible, a shared 3.0 m (10 ft) non-raised median shoulder may be used. In such cases, passing should be prohibited and cross hatching or other delineation should be employed[6]. A general summary of the cross-section guidelines for Two-way barrier-separated HOV lanes is provided in Table 4-4.

Table 4-4. Summary of Cross-Section Guidelines for Two-Way Barrier-Separated HOV Lanes.

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	13.8 m (46 ft)	11.4 m (38 ft)
Lane Width	3.6 m (12 ft) per lane	3.6 m (12 ft) per lane
Shoulder/Buffer Width (Right, Left)	1.8 m (6 ft), 0.6 m (2 ft) per direction	0.6 m (2 ft) per direction, 3 m (10 ft) shared buffer/shoulder
Internal Lane Separation	0.6 m (2 ft) median barrier	Median buffer (see above)

Design Tradeoffs

Proper consideration of safety in HOV-facility design entails full examination of potential alternatives to design compromises. However, if the HOV lane is a retrofit design being implemented in a constrained right of way, the use of minimum design standards or exceptions may be acceptable. Decisions to adopt facility designs that do not meet full AASHTO standards should be carefully scrutinized by project stakeholders with safety being the foremost consideration. An engineering safety review should be undertaken to determine the potential safety impact of any design compromises adopted. Table 4-5 presents a prioritized list of design tradeoffs that may be considered for two-way barrier-separated HOV facilities that cannot be constructed to desirable design standards.

Table 4-5. Prioritized Design Tradeoffs for Two-Way Barrier-Separated HOV Lanes[6].

Ordered Sequence	Cross-Section Design Change
First	Reduce HOV envelope to 12.6 m (42 ft) according to the middle schematic with 0.6 m (2 ft) offset to middle barrier.
Second	Reduce freeway left lateral clearance to no less than 0.6 m (2 ft).
Third	Reduce freeway right lateral clearance (shoulder) from 3.0 m (10 ft) to 2.4 m (8 ft).
Fourth	Reduce HOV-lane width to no less than 3.3 m (11 ft) (some agencies may prefer reversing the fourth and fifth tradeoffs when buses or trucks are projected to use the HOV lane).
Fifth	Reduce selected general-purpose lane widths to no less than 3.3 m (11 ft) (leave at least one 3.6 m [12 ft] outside lane for trucks).
Sixth	Reduce freeway right lateral clearance (shoulder) from 2.4 m (8 ft) to 1.2 m (4 ft).
Seventh	Convert barrier shape at columns to a vertical face.

Note: The ordered sequence presented here is only an example list. Some states may prefer a different sequence.

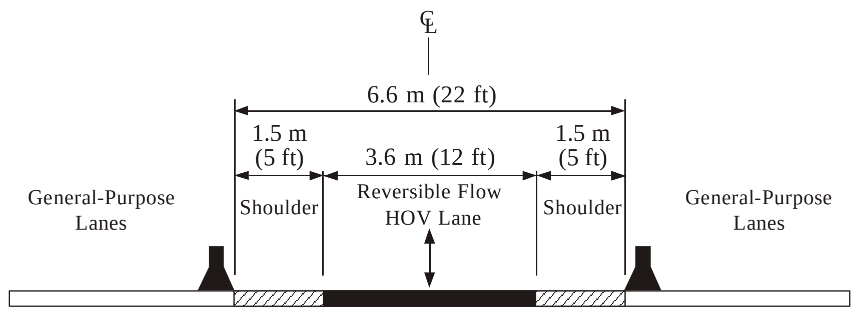
Reversible Barrier-Separated HOV Lanes

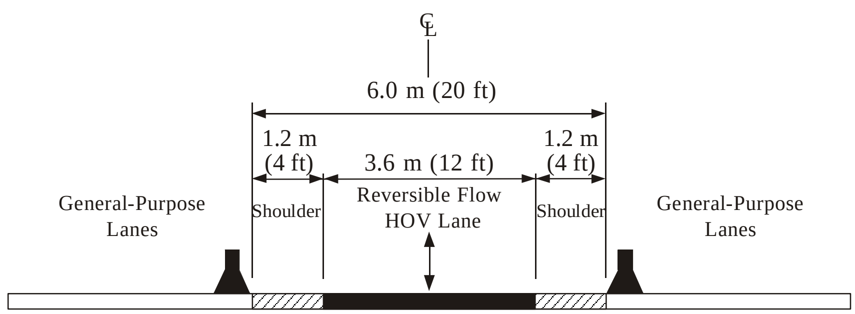
Facility Cross Section

Single-lane reversible barrier-separated HOV facilities are located within the freeway right of way, offer one lane of travel in the peak direction, and are physically separated from the general-purpose lanes by concrete barriers. Figure 4-3 shows desirable and minimum cross sections for this type of facility. The desirable design calls for an envelope of 6.6 m (22 ft), while the minimum design can be accommodated in a 6.0 m (20 ft) envelope. Standard 3.6 m (12 ft) lane widths of should be used. Desirable and minimum lateral clearances are 1.5 m (5 ft) and 1.2 m (4 ft) respectively. The even distribution of clearances on either side of the travel lane enhances safety by discouraging passing. This design also provides for the largest barrier offset in both directions, while permitting motorists to maneuver around disabled vehicles that are parked to one side of the facility. A general summary of the cross-section guidelines for a single-lane reversible barrier-separated HOV facility is provided in Table 4-6.

Table 4-6. Summary of Cross-Section Guidelines for a Single-Lane Reversible Barrier-Separated HOV Facility.

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	6.6 m (22 ft)	6.0 m (20 ft)
Lane Width	3.6 m (12 ft)	3.6 m (12 ft)
Shoulder/Buffer Width (Right, Left)	1.5 m (5 ft), 1.5 m (5 ft)	1.2 m (4 ft), 1.2 m (4 ft)
Internal Lane Separation	N/A	N/A





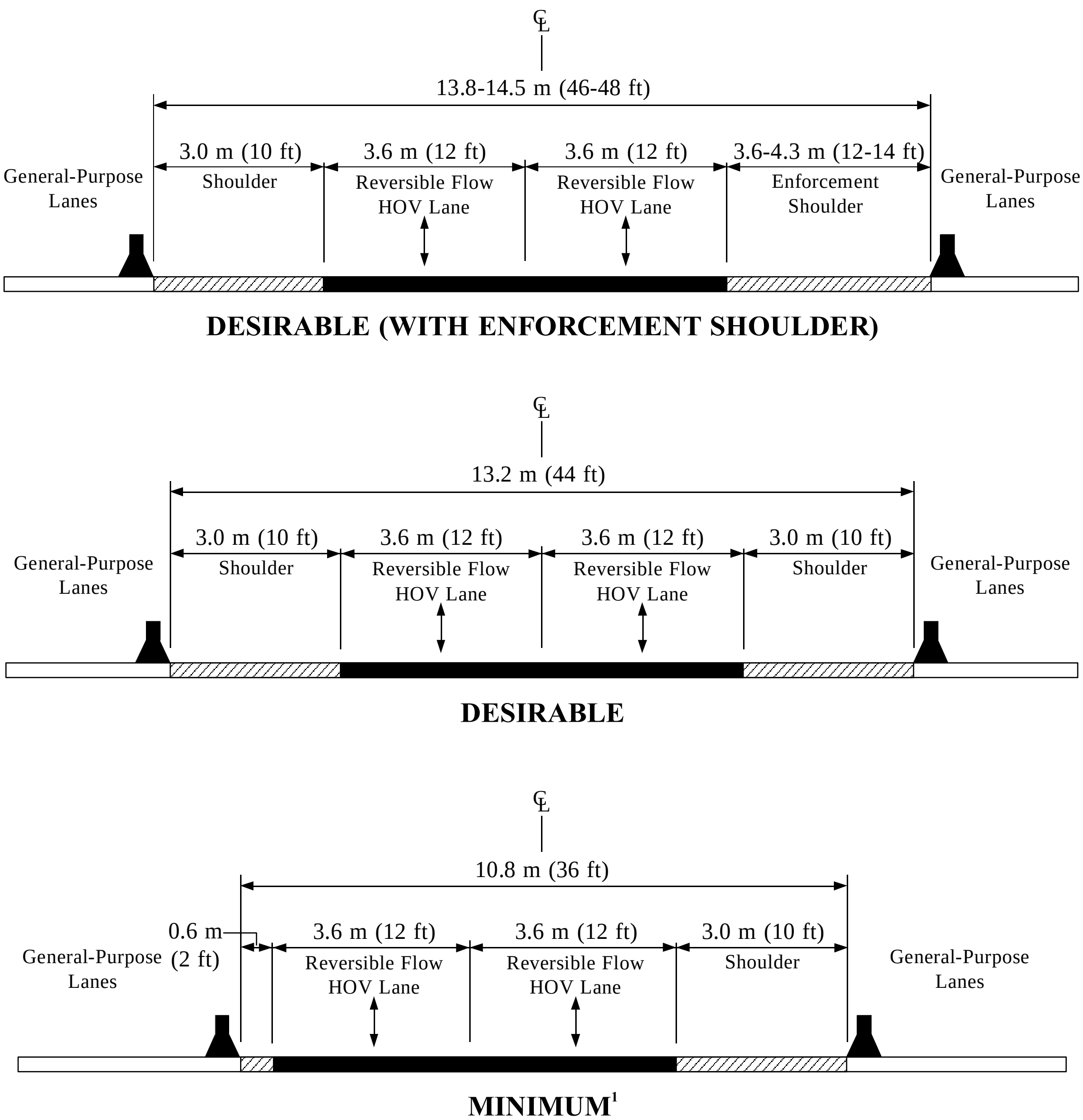
[1] HOV envelopes over 6.6 m (22 ft) may invite passing along the single-lane facility. The shoulder width is divided evenly to allow vehicles to travel in both directions with the widest offset to the barrier. A full breakdown shoulder is not provided although vehicles can still maneuver around disabled vehicles. Enforcement of this facility is performed at the ends and access locations.

[2] Operational treatments should be incorporated if the minimum design cross section is used. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility.

[3] The width of this cross section provides the minimum space required for a bus to pass a disabled bus at slow speed.

Figure 4-3. Examples of Cross Sections for Single-Lane, Reversible Barrier-Separated HOV Facilities[6].

Apart from the number of lanes offered, the primary design difference between single and two-lane reversible barrier-separated HOV facilities is the width of their shoulders. Desired and minimum design envelopes required for a two-lane facility are illustrated in Figure 4-4.



[1] Operational treatments should be incorporated if the minimum design cross section is used. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility.

Figure 4-4. Examples of Cross Sections for Two-Lane, Reversible Barrier-Separated HOV Facilities[6].

An envelope of 13.8 to 14.5 m (46 to 48 ft) is needed to incorporate a full shoulder on one side and an enforcement shoulder on the other. The minimum design can be accommodated in an envelope of 10.8 m (36 ft). This design includes a 3.0 m (10 ft) right-hand breakdown shoulder so that disabled vehicles can be safely parked without obstructing the travel lanes. A 0.6 m (2 ft) lateral barrier offset is provided on the other side. This design is less safe because it reduces emergency maneuvering room and requires violators and disabled vehicles in the left lane to merge across traffic to reach the shoulder. A general summary of the cross-section guidelines for a two-lane reversible barrier-separated HOV facility is provided in Table 4-7.

Table 4-7. Summary of Cross-Section Guidelines for a Two-Lane Reversible Barrier-Separated HOV Facility.

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	13.2 to 14.5 m (44 to 48 ft)	10.8 m (36 ft)
Lane Width	3.6 m (12 ft) per lane	3.6 m (12 ft) per lane
Shoulder/Buffer Width (Right, Left)	3.0 to 4.3 m (10 to 14 ft) Depends on the use of enforcement shoulder, 3.0 m (10 ft)	3.0 m (10 ft), 0.6 m (2 ft)
Internal Lane Separation	None	None

Design Tradeoffs

Table 4-8 presents a prioritized list of design tradeoffs that may be considered for single and two-lane reversible barrier-separated HOV facilities that cannot be constructed to desirable design standards.

Table 4-8. Prioritized Design Tradeoffs for Reversible Barrier-Separated HOV Facilities[6].

Ordered Sequence	Cross-section Design Change
First	Reduce single-lane HOV envelope to no less than 6.0 m (20 ft) or reduce two-lane envelope to no less than 10.8 m (36 ft).
Second	Reduce freeway left lateral clearance to no less than 0.6 m (2 ft).
Third	Reduce freeway right lateral clearance (shoulder) from 3.0 m (10 ft) to 2.4 m (8 ft).
Fourth	Reduce HOV-lane width to no less than 3.3 m (11 ft) (some agencies may prefer reversing the fourth and fifth tradeoffs when buses or trucks are projected to use the HOV lane).
Fifth	Reduce selected general-purpose lane widths to no less than 3.3 m (11 ft) (leave at least one 3.6 m [12 ft] outside lane for trucks).
Sixth	Reduce freeway right lateral clearance (shoulder) from 2.4 m (8 ft) to 1.2 m (4 ft).
Seventh	Convert barrier shape at columns to a vertical face.

Note: The ordered sequence presented here is only an example list. Some states may prefer a different sequence.

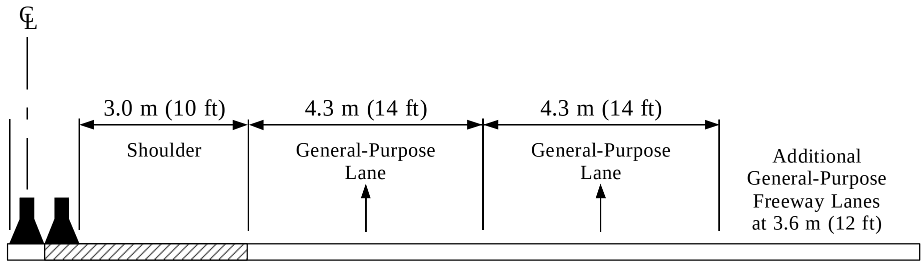
Contraflow HOV Lanes

Facility Cross Section

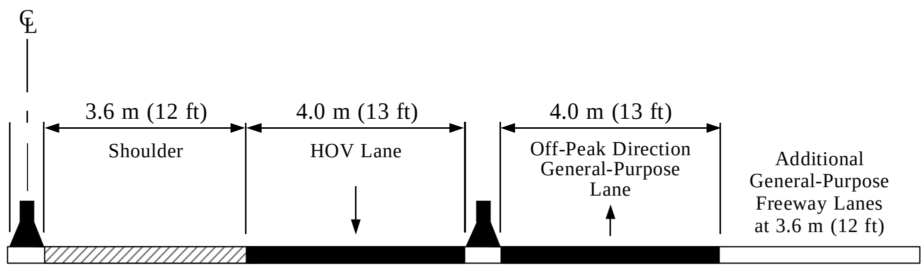
Contraflow HOV lanes utilize surplus roadway capacity in the off-peak direction of travel to satisfy excess demand in the peak direction. Most contraflow facilities in freeway settings are designed with moveable concrete barriers to separate opposing traffic flows when the facility is in operation. A special "zipper truck" is used to move the barriers into position between peak traffic periods (see Figure 4-5).

Figure 4-5. Transfer of Moveable Barrier for Contraflow Operations.

Desirable and minimum designs for contraflow facilities in freeway environments are illustrated in Figures 4-6 and 4-7.



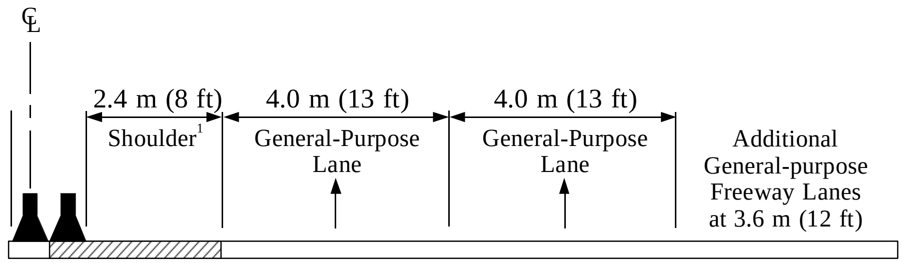
DESIRABLE[1] (NON-OPERATING) MOVEABLE BARRIER SEPARATED



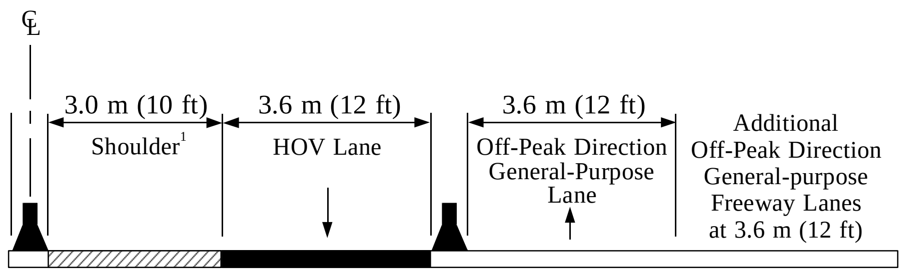
DESIRABLE[1] (OPERATING) MOVEABLE BARRIER SEPARATED

[1] Enforcement of this facility is performed at the ends and access locations.

Figure 4-6. Desirable Cross Sections for Contraflow HOV Facilities[6].



MINIMUM[1] (NON-OPERATING) MOVEABLE BARRIER SEPARATED



MINIMUM[1] (OPERATING) MOVEABLE BARRIER SEPARATED

[1] Operational treatments should be incorporated if the minimum design cross section is used or no continuous shoulder exists. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility.

Figure 4-7. Minimum Cross Sections for Contraflow HOV Facilities[6].

Due to the additional space needed to safely accommodate the moveable barrier, the desirable width of the contraflow lane and the lane adjacent to it is larger than normal. Desirable lane widths are 4.0 m (13 ft) during operation and 4.3 m (14 ft) during non-operation. The desirable shoulder width is 3.6 m (12 ft) when the facility is operating and 3.0 m (10 ft) when it is not. The minimum cross section includes 2.4 m (8 ft) shoulder widths and 4.0 m (13 ft) lane widths during non-operational periods. The minimum cross section during operational periods includes a 3.0 m (10 ft) shoulder and 3.6 m (12 ft) lane. A general summary of the cross-section guidelines for a freeway contraflow HOV lane is provided in Table 4-9.

Very few contraflow HOV lanes on arterial streets are currently in operation in the United States. Where these facilities have been implemented, they do not entail the use of moveable concrete barriers. The width of contraflow HOV lanes on arterial streets depends on the volume of pedestrian traffic adjacent to the lane. Standard lane widths range from a minimum of 3.3 m (11 ft) to 4.3 m (14 ft) in areas with significant pedestrian movements.

Table 4-9. Summary of Cross-Section Guidelines for a Freeway Contraflow HOV Lane.

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	7.6 m (25 ft) Operating	6.6 m (22 ft) Operating
Lane Width	4.0 m (13 ft)	3.6 m (12 ft)
Shoulder/Buffer Width (Right, Left)	None, 3.6 m (12 ft)	None, 3.0 m (10 ft)
Internal Lane Separation	None	None

Access and Enforcement

Freeway contraflow lanes are accessed via at-grade median crossovers. Due to the complexity of these access points and barrier separation of the contraflow facility, a single entrance and exit are provided and enforcement is normally confined to the ingress location. Several safety considerations should be accounted for in the access and enforcement design process:

- Where possible, crossovers should be located where natural slowdowns occur, such as an approach to a central business district. This reduces high-speed weaving maneuvers and the disruption of traffic flow.
- Advance signing in the peak and off-peak direction is required to indicate facility operations and oncoming traffic (when applicable).
- MUTCD signing and physical gates/barriers that prevent wrong-way movements are particularly important on contraflow facilities, as motorists may not be familiar with the function of the facility or its operations schedule.
- Enforcement activities should occur in a designated zone at the entrance to the facility where officers can redirect ineligible users and motorists that may have inadvertently entered the lane. Adequate lane width (4.3 m [14 ft]) should be provided for enforcement activities at these sites.

Additional Safety Considerations Associated with Facility Design

Reversing the direction of traffic lane on a freeway or arterial street involves obvious safety considerations. These and other operational elements are examined in the following chapter. Design considerations associated with contraflow HOV lanes also have potential safety implications. A viable contraflow design typically requires at least a 60/40 directional split in peak/off-peak traffic. Corridors with more balanced traffic flows generally lack sufficient off-peak capacity to safely implement a contraflow lane. The danger of reducing off-peak capacity for contraflow-lane implementation is evidenced by higher crash rates in the off-peak direction as compared with the peak direction for some facilities[8].

Contraflow lanes on arterial streets should generally be reserved for buses only. This avoids safety problems associated with higher traffic volumes and the use of the facility by drivers that lack special training. Transit drivers must exercise extra caution on arterial-street contraflow facilities because pedestrians often do not anticipate contraflow movements. Highly visible signage, pedestrian fencing, and lane control signals can be used to reduce pedestrian-HOV conflicts.

Access Treatments for Barrier-Separated Facilities

A number of direct and at-grade access treatments can be used with these facility types. The selection and design of access treatments involves consideration of various project factors. Flyover ramps and T-ramps are preferred for barrier-separated HOV lanes from a safety perspective. These direct-access options eliminate the need for vehicles to weave across multiple general-purpose lanes while rapidly accelerating or decelerating to access the HOV lane or exit the freeway. This allows for greater HOV-lane volumes and fewer disruptions of general-purpose traffic. However, direct-access treatments are expensive to construct and require additional right of way.

At-grade access treatments may be considered when cost or right-of-way limitations preclude the use of direct-access designs. To improve safety and eliminate wrong-way movements, at-grade access treatments should incorporate:

- Robust signing, pavement markings, and access barriers/gates
- Signing that begins at least 1.6 km (1.0 mile) before the entry of the facility and conforms to MUTCD and state/local guidelines[6]
- Proper spacing vis-à-vis freeway interchanges so that vehicles have sufficient room to safely enter or exit the HOV facility and freeway
- Emergency access gates at frequent intervals so that disabled vehicles can be removed from the facility safely and quickly

The design and location of emergency access gates on barrier-separated HOV lanes involves consideration of safety. While these treatments are primarily intended to provide emergency access to tow trucks and first responders, they may also be used to provide an exit for HOV traffic trapped in a queue behind a disabled vehicle blocking the lane. Safe and effective emergency gate designs incorporate several features:

- Protection against vehicle impacts at high speeds
- Substantial barrier opening (usually 12.2 m [40 ft] or greater)
- Location where horizontal and vertical HOV-lane alignments permit safe operation
- Strategic spacing between narrow HOV-lane sections

Emergency access gates are intended to provide access to the HOV lane for first responders, but that may also provide an "escape route" for vehicles trapped in a queue behind an incident that is blocking the lane.

- Inconspicuous design and location to reduce potential for driver confusion or wrong-way movements
- Easily and quickly retractable
- Minimum space requirements when retracted
- Manual and remote/electronic operations

Special attention must be paid to potential access and enforcement-area safety hazards on reversible HOV lanes that may not arise on facilities that operate in a single direction. This includes installing crash cushions on concrete barrier terminals to reduce the severity of vehicle-barrier terminal collisions (see Figure 4-8).

Figure 4-8. Crash Attenuation for Exposed Barrier Ends on Reversible HOV-Lane.

Enforcement Sites for Barrier-Separated Facilities

The design of enforcement sites can impact the safety of barrier-separated HOV facilities for motorists and enforcement personnel alike. Poorly designed enforcement areas create driver confusion and unsafe conditions for officers trying to identify the number of occupants in passing vehicles. HOV enforcement without proper refuge areas can also disrupt traffic and lead to unsafe conditions on the HOV lane[17]. Reversible barrier-separated HOV lanes are usually enforced at ingress and egress ramps. Speed limits at these sites are typically 70 km/h (45 mph) or less, enabling safer, more effective enforcement. Utilization of gore areas and closed sections of ramps on reversible HOV facilities minimizes disruption of legitimate traffic and further enhances safety. Figure 4-9 shows an example of enforcement activities in the unused portions of a reversible HOV-lane ramp.

Figure 4-9. Enforcement on Unused Portion of Reversible HOV-Lane Ingress/Egress Ramp.

Adequate lighting at ingress and egress points also enhances motorist and officer safety and facilitates vehicle-occupancy determination. The length of enforcement zones and storage areas depends on site-specific considerations such as the violation rate, traffic volume, enforcement presence, and vehicle mix. The following design guidelines apply to low-speed enforcement zones on reversible HOV facilities[6]:

- Be at least 30 m (100 ft) in length and preferably up to 60 m (200 ft) on high-volume facilities, not including approach and departure tapers
- Be at least 3.6 to 4.3 m (12 to 14 ft) wide
- Have an approach taper of 9.1 m (2:1 or approximately 30 ft)
- Have a departure taper of 45.7 m (10:1 or approximately 150 ft) to allow for acceleration into the lane

Two-way barrier-separated HOV facilities normally offer a greater number of access points than reversible lanes. In addition, there are no unused portions of access ramps for verifying vehicle occupancies. These factors complicate enforcement and may require enforcement sites to be spread along the facility as opposed to being clustered at ingress and egress locations. Enforcement shoulder widths of 3.6 to 4.3 m (12 to 14 ft) are necessary on two-way facilities in order for violators to be safely segregated, ticketed, and reintegrated into the traffic stream.

The design of barrier-separated HOV facilities can have safety implications beyond those described above. Practitioners and researchers have identified safety effects specifically related to barrier-separated HOV-lane designs. These issues, summarized below, augment the safety considerations in HOV-lane operations that are examined in Chapter 5 of the handbook.

Safety Advantages of Barrier-Separated HOV Facilities

There is a general consensus that barrier-separated HOV facilities offer a critical safety advantage over buffer-separated and non-separated HOV lanes:

- Concrete barriers protect traffic in the HOV lane and general-purpose lanes from the considerable speed differential that may exist between the two traffic streams.

- Collisions that occur in the general-purpose lanes do not, therefore, typically disrupt the operation of the barrier-separated facility[7].

In 2003, a study of crash data collected before and after buffer and barrier-separated HOV lanes were implemented in Dallas, Texas, indicated that, unlike the buffer-separated lanes, the barrier-separated facility did not have a negative impact on injury crash rates[10]. A 1992 HOV-lane safety study conducted by California Polytechnic State University reported similar findings. Crash rates were evaluated before and after installation of HOV facilities with and without physical separation. On projects where no physical separation existed between the HOV and general-purpose traffic lanes, crash levels increased dramatically during the first year of operation. These rates subsequently declined but remained significantly higher than pre-project levels. Where the HOV lane was physically separated from the general-purpose lanes, no upward surge in crash rates was discernable[11].

Safety Disadvantages of Barrier-Separated HOV Facilities

Notwithstanding their overall superior safety performance, barrier-separated HOV lanes may also confer potential safety disadvantages in certain cases:

- The limited-access operation of barrier-separated HOV facilities concentrates weaving in the general lanes to particular locations upstream of HOV access terminals and downstream of HOV egress terminals[8]. Weaving across congested general-purpose lanes to and from these access points is a relatively complicated maneuver that degrades safety by exacerbating vehicle conflicts. This problem is applicable to barrier and buffer-separated facilities.

- A vehicle that becomes disabled on the interior general-purpose lane may have to traverse several lanes of traffic to reach a refuge area on the right-hand shoulder of the freeway as a result of HOV-lane barrier separation.

- Close proximity of the median barrier to general-purpose traffic can lead to multiple-vehicle crashes if a vehicle strikes the wall and is deflected back into the traffic lanes[8].

- Median or lateral barriers and glare screens may obstruct sight distances around curves and at other locations. These treatments may have to be adjusted or removed in specific areas for safety purposes[12].

- The inability of a vehicle to exit a barrier-separated facility in the event of an emergency can also disrupt operations and generate secondary incidents, particularly if there is limited space within the facility.

On completely separated facilities, the HOV roadway has many characteristics of a tunnel because once on the facility, vehicles are irrevocably committed to driving it until the next exit. Incidents occurring in these "pipeline" sections can seriously interfere with traffic flow, if roadway and shoulder widths are insufficient to allow storage of disabled vehicles[8]. Motorists on barrier-separated facilities often travel at much higher rates of speed than vehicles in adjacent general-purpose lanes. Because drivers in the HOV lane do not generally expect to encounter stopped traffic, slowing down and maneuvering around a disabled vehicle can be an unexpected and dangerous event.

Practitioner Safety Concerns for Barrier-Separated HOV Lanes

Practitioners, consultants, and researchers involved in HOV projects have unique insight into the safety implications of facility design. As part of the above-mentioned Dallas HOV-lane crash study conducted in 2003, a safety survey was distributed to 95 transportation professionals with HOV experience. A total of 23 surveys were returned, yielding a response rate of 24 percent. Table 4-10 shows the level of concern that the 23 survey respondents had with respect to the safety of various aspects of barrier-separated HOV facilities.

Table 4-10. Practitioner Safety Issues for Barrier-Separated HOV Lanes-Level of Concern [10]

Issue	High	Medium	Low	No	N/A	No Response	Total
Operational Issues at Ingress/Egress Locations	2	5	6	2	3	5	23
Lack of or Reduced Inside Shoulder Width	4	3	4	3	3	6	23
Reduced HOV-Lane Widths	0	3	5	6	3	6	23
Disabled Vehicles on HOV Lane	3	4	4	4	2	6	23
Wrong-Way Movements in HOV Lanes	3	2	3	6	3	6	23

The respondents' rankings and written comments indicated that the lack of, or reduced, inside shoulder within the HOV lane negatively impacted facility safety. Disabled vehicles could not be safely parked, and incident management activities were complicated due to the presence of the barriers. The potential for queuing at ingress and egress locations and wrong-way movements were also cited as important safety considerations. Design alternatives to address these problems include:

- Larger shoulder widths (where possible)

- Designated breakdown areas within the facility where wide continuous shoulders are not feasible (helps offset safety impact of narrow HOV-lane shoulders[10])
- Proper signage and redundant gates/barriers to prevent wrong-way movements and reduce crashes related to excessive speed and loss of lane control

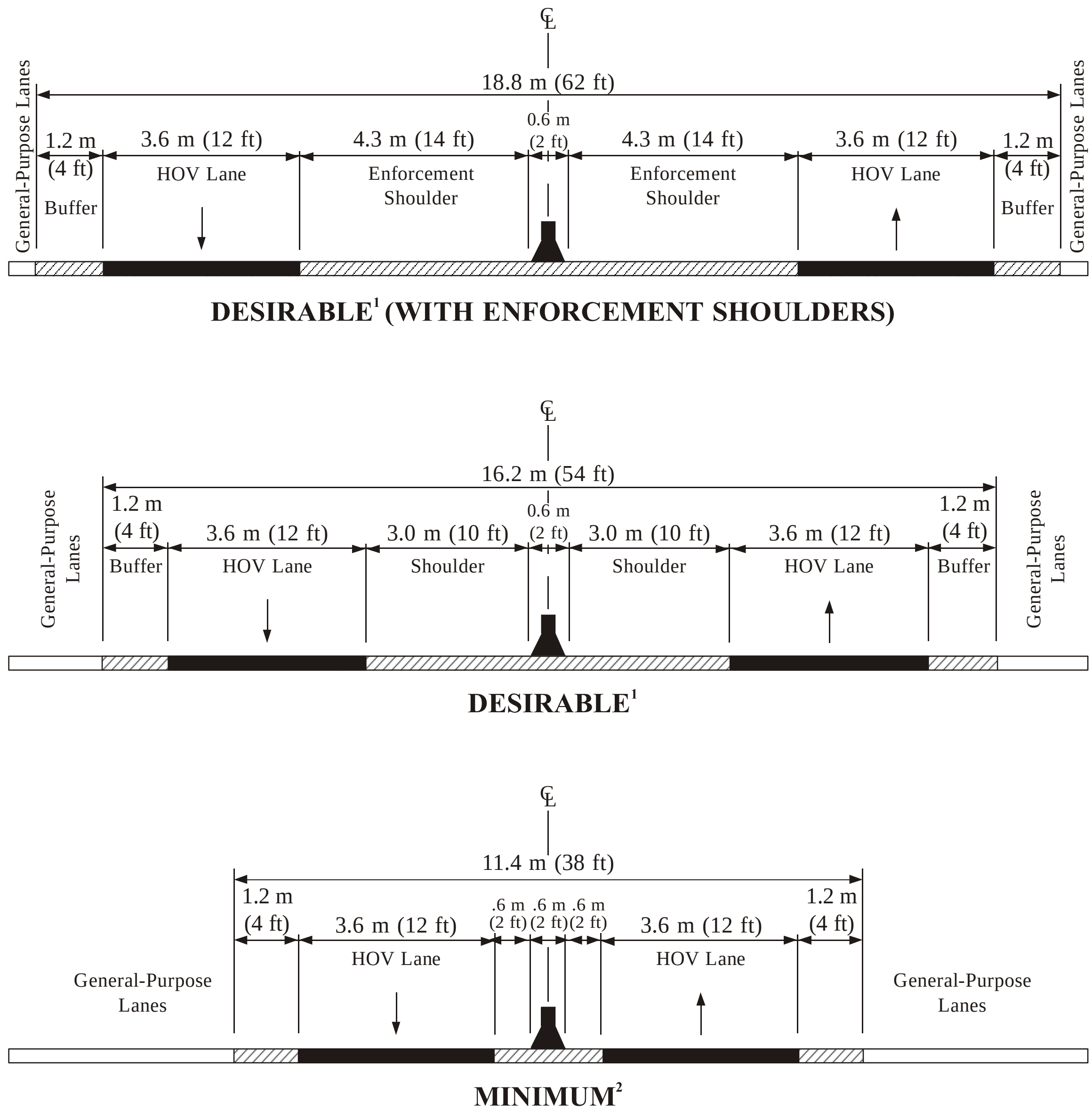
Non-Barrier -Separated HOV Facilities

The sections below describe the design elements for the different types of non-barrier-separated HOV facilities, followed by a discussion of safety-related issues associated with non-barrier-separated lanes based on research and operator experience.

Concurrent Buffer-Separated HOV Lanes

Facility Cross Section

Concurrent buffer-separated facilities are freeway HOV lanes that offer a priority lane of travel in the same direction as the general-purpose lanes. They are typically constructed using the inside shoulder or median of the freeway right of way, and are separated from general-purpose lanes by a painted buffer. Cross-section designs for this type of facility are illustrated in Figure 4-10. The desirable envelope for two-way operations is 16.2 to 18.8 m (54 to 62 ft). The minimum envelope is 11.4 m (38 ft). Standard lane and buffer widths are 3.6 m (12 ft) and 1.2 m (4 ft), respectively. Shoulder widths of 3.0 to 4.3 m (10 to 14 ft) are desirable, depending on whether a regular or enforcement shoulder is provided. A general summary of the cross-section guidelines for concurrent buffer-separated HOV lanes in both directions is provided in Table 4-11.



[1] Enforcement personnel should be consulted to determine how and where they intend to identify and issue citations to violators. This will affect the design. Directional or bi-directional enforcement areas that are barrier-protected may be incorporated into these cross sections.

[2] Operational treatments should be incorporated if the minimum design cross section is used. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility. The designer must also consider the design exception requirements.

Figure 4-10. Examples of Cross Sections for Concurrent Buffer-Separated HOV Facilities[6].

Table 4-11. Summary of Cross-Section Guidelines for Concurrent Buffer-Separated HOV Lanes (Two-Way Operations).

Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	16.2 to 18.8 m (54 to 62 ft)	11.4 m (38 ft)
Lane Width	3.6 m (12 ft) per lane	3.6 m (12 ft) per lane
Shoulder/Buffer Width (Right, Left)	1.2 m (4 ft), 3.0 to 4.3 m (10 to 14 ft) per direction. Depends on the use of enforcement shoulder	1.2 m (4 ft), 0.6 m (2 ft) per direction
Internal Lane Separation	0.6 m (2 ft) barrier between lanes	0.6 m (2 ft) barrier between lanes

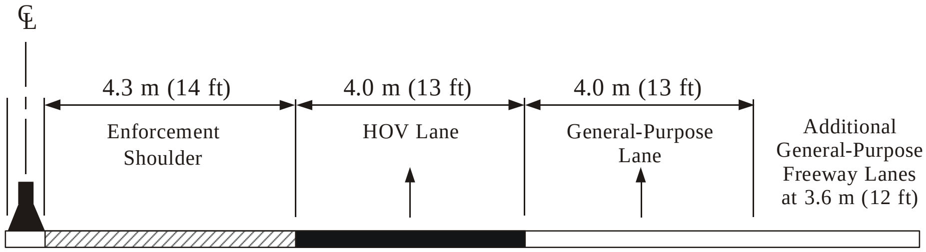
Concurrent Non-Separated HOV Lane

Facility Cross Section

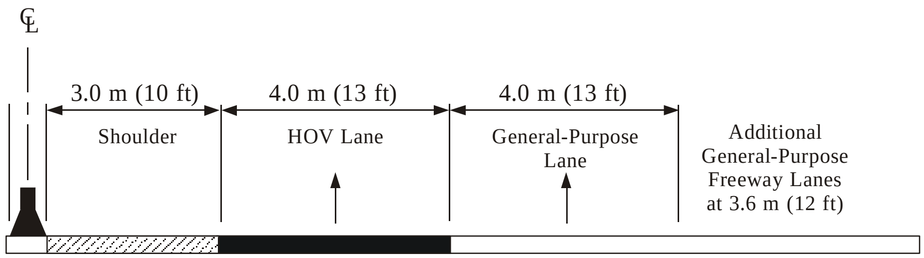
Concurrent non-separated HOV lanes often revert back to general-purpose use during off-peak periods. For this reason, they do not usually incorporate a buffer between the HOV facility and general-purpose lanes. Desirable and minimum designs for concurrent non-separated facilities on freeways are illustrated in Figure 4-11. The desirable width of the HOV lane and the adjacent general-purpose lane is 4.0 m (13 ft). The added 0.3 m (1 ft) of lane width in the facility design is a safety measure to compensate for the lack of a buffer. Minimum lane width for freeway applications is 3.6 m (12 ft), with a 0.6 m (2 ft) lateral offset from the median barrier used instead of a shoulder. A general summary of the cross-section guidelines for concurrent non-separated HOV lanes is provided in Table 4-12.

Table 4-12. Summary of Cross-Section Guidelines for Concurrent Non-Separated HOV Lane.

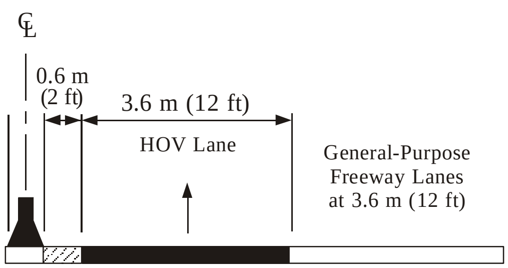
Cross-Section Element	Desired Guideline	Minimum Guideline
Envelope	7.0 to 8.3 m (23 to 27 ft)	4.2 m (14 ft)
Lane Width	4.0 m (13 ft)	3.6 m (12 ft)
Shoulder/Buffer Width (Right, Left)	None, 3.0 to 4.3 m (10 to 14 ft) Depends on the use of enforcement shoulder	None, 0.6 m (2 ft)
Internal Lane Separation	N/A	N/A



DESIRABLE[1] (WITH ENFORCEMENT SHOULDERS)



DESIRABLE[1]



MINIMUM[1,2]

[1] This cross section has been used when the HOV lane will convert to general-purpose traffic use during non-peak periods.

[2] Operational treatments should be incorporated if the minimum design cross section is used. The minimum cross section should be used as an interim project or over short distances. Increased enforcement and incident management programs should be implemented to successfully operate the facility. The designer must also consider the design exception requirements.

Figure 4-11. Examples of Cross Sections for Concurrent Non-Separated HOV Facilities[6].

Design Tradeoffs

Tables 4-13 and 4-14 present prioritized lists of design tradeoffs that may be considered to accommodate concurrent buffer-separated and non-separated freeway HOV facilities in constrained rights of way.

Table 4-13. Example Design Tradeoffs for Concurrent Buffer-Separated HOV Lanes[6].

Ordered Sequence	Cross-Section Design Change
First	Reduce HOV envelope general-purpose lanes (including buffers) to 11.4 m (38 ft).
Second	Reduce freeway right lateral clearance (shoulder) from 3.0 m (10 ft) to 2.4 m (8 ft).
Third	Reduce HOV-lane width to no less than 3.3 m (11 ft) (some agencies may prefer reversing the third and fourth tradeoffs when buses or trucks are projected to use the HOV lane).
Fourth	Reduce selected general-purpose lane widths to no less than 3.3 m (11 ft) (leave at least one 3.6 m [12 ft] outside lane for trucks).
Fifth	Reduce freeway right lateral clearance (shoulder) from 2.4 (8 ft) to 1.2 m (4 ft).
Sixth	Convert barrier shape at columns to a vertical face.

Note: The ordered sequence presented here is only an example list. Some states may prefer a different sequence.

Table 4-14. Example Design Tradeoffs for Concurrent Non-Separated HOV Facilities[6].

Ordered Sequence	Cross-Section Design Change
First	Reduce left lateral clearance to 0.6 m (2 ft) and all lanes (HOV and general-purpose) to 3.6 m (12 ft).
Second	Reduce freeway right lateral clearance (shoulder) from 3.0 m (10 ft) to 2.4 m (8 ft).
Third	Reduce HOV-lane width to no less than 3.3 m (11 ft) (some agencies may prefer reversing the third and fourth tradeoffs when buses or trucks are projected to use the HOV lane).
Fourth	Reduce selected general-purpose lane widths to no less than 3.3 m (11 ft) (leave at least one 3.6 m [12 ft) outside lane for trucks).
Fifth	Reduce freeway right lateral clearance (shoulder) from 2.4 m (8 ft) to 1.2 m (4 ft).
Sixth	Convert barrier shape at columns to a vertical face.

Note: The ordered sequence presented here is only an example list. Some states may prefer a different sequence.

It should be noted that cross-section design compromises and the order in which they are considered frequently vary by agency, region, or facility. For example, the California Department of Transportation (Caltrans) uses different cross-section tradeoffs than those recommended by AASHTO for non-separated HOV facilities.

Safety Considerations in the Design of Arterial-Street HOV Lanes

An arterial-street HOV facility is essentially a concurrent non-separated HOV lane in an arterial-street environment. Various facility cross sections and treatments have been implemented and the safety considerations associated with them are diverse. This section highlights key safety issues with broad relevance.

The foremost design consideration characterizing arterial-street HOV lanes is the potential sources of conflict. These include:

- Intersections
- Driveways
- Turning vehicles
- Parked vehicles
- Bus stops
- Pedestrians
- Bicyclists

Warning signs, top-of-curb markings, pavement markings, and pedestrian fencing are common design techniques used to alert motorists, pedestrians, and bicyclists to these conflicts. "Restricted lane ahead" signs should be placed well in advance of arterial HOV lanes to allow general traffic to safely transition into another lane[6].

The desired width of a concurrent-flow HOV lane in an arterial environment depends primarily on the degree of bicycle traffic on the roadway and pedestrian traffic on adjacent sidewalks.

- Safe arterial-street lane widths generally range from a minimum of 3.3 m (11 ft) to 4.3 m (14 ft) for lanes next to sidewalks with significant pedestrian movements.

- Facility design may also entail consideration of bicycle traffic. Permitting bicyclists to travel on an HOV lane or in the HOV envelope has important design and safety implications. The AASHTO *Guide for the Development of Bicycle Facilities* recommends paved arterial-street shoulders that are between 1.2 m (4 ft) and 1.5 m (5 ft) wide to accommodate bicycle travel[18].

- If bicyclists are permitted in the lane of travel itself, the lane should be adjusted by the appropriate amount. Alternatively, a separate bicycle-only lane next to the HOV lane may be provided.

Special attention should be paid to pavement surfaces on arterial HOV lanes that accommodate bicyclists. These surfaces should be smooth and free of potholes and ruts, and the facility should be regularly swept to clear debris[6]. Potential obstacles such as raised pavement markers, drainage grates, and manhole covers that may cause unexpected maneuvers by bicyclists should be removed, relocated, or more clearly marked. Table 4-15 summarizes other potential design and operational safety concerns that may arise on arterial-street HOV lanes and identifies possible approaches for addressing them.

Table 4-15. Safety Concerns and Countermeasures for Arterial-Street HOV Lanes[16].

Potential Safety Concerns	Techniques to Address
Turning movements at intersections	• Restrict turns by general-purpose vehicles during HOV operating hours • Allow turns by general-purpose vehicles at selected intersections only
Turning movements at driveways	• Restrict turns by general-purpose vehicles during HOV operating hours • Limit access points to adjacent land uses during HOV operating hours • Provide alternative access points for general-purpose vehicles
On-street parking	• Restrict on-street parking during HOV operating hours • Provide alternate parking spaces
On-street delivery vehicles	• Restrict on-street delivery vehicles during HOV operating hours • Provide alternate locations for delivery vehicles and allow access during non-operating hours
Pedestrian conflicts	• Provide well-marked crosswalks at intersections • Set signal timing to provide adequate pedestrian crossing time • Provide center median waiting area if needed • Take special measures, such as reducing speed limits in school, hospital, and other zones
Bicycle conflicts	• Provide bicycle lane in areas with high bicycle volumes

Access Treatments for Non-Barrier-Separated HOV Facilities

Two access designs, limited (also called restricted) and unlimited (also called continuous or contiguous), are used with concurrent HOV lanes.

Unlimited Access

Unlimited access is often employed on non-separated concurrent facilities that operate on a part-time basis. Because these facilities automatically switch between HOV operations and mixed use according to the time of day, restrictive access treatments are not typically used. Vehicles are allowed unimpeded movement to and from the HOV lane anywhere along its length. Unlimited access treatments are characterized by the following:

- No weave, acceleration, or deceleration lane (eligible vehicles enter and leave the facility as though it were a general-purpose lane)

- Conspicuous signing and pavement markings (such as double skip striping) are utilized to avoid driver confusion regarding lane designation

Limited Access

Limited-access treatments confine legal HOV ingress and egress maneuvers to specific locations. A buffer or barrier is used to separate the HOV facility from the adjacent general-purpose lane between access points. Separate ingresses and egresses points may be provided or a single access opening may serve both purposes. Limited-access treatments are characterized by the following:

- Acceleration, deceleration, or weave lanes may be provided if available right-of-way exists.
- Desirable length of buffer openings is 400 to 460 m (1,300 to 1,500 ft).
- Vertical alignment and corresponding acceleration and deceleration requirements are taken into consideration when designing and locating individual access points.
- Advance signing is used to reduce abrupt and unexpected weaving maneuvers at access locations.
- Ingress/egress points are generally provided at freeway-to-freeway interchanges and at other locations that can safely accommodate merging and weaving.

Determination of additional access locations at state highways and major arterials should involve consideration of traffic volumes, connectivity, impact on adjoining streets, ability of drivers to weave across general-purpose lanes to access the HOV lane and freeway exits, and related safety issues. A weave analysis should be conducted to ensure that access designs and locations are safe and appropriate for anticipated traffic levels. Further discussion of the safety implications of access treatments is provided in the related analysis of buffer separation and non-separation below.

Direct Connect Ramps

In an effort to enhance safety and isolate its HOV facilities more completely from general-purpose traffic, the California Department of Transportation has invested in direct HOV-lane access ramps and freeway-to-freeway connectors[14]. This form of access, while expensive, provides safety benefits by eliminating the need for HOV traffic to weave across the general-purpose lanes to enter and exit the HOV facility.

Buffer Separation versus Non-Separation

Buffer-separated and non-separated HOV facilities are relatively inexpensive to implement, can be accommodated in constrained rights of way, and offer operational flexibility. However, their use implies unique safety considerations. According to the California Department of Transportation's *HOV Guidelines for Planning, Design, and Operations (1991)*, buffer-separated HOV facilities may provide various safety advantages compared to non-separated HOV lanes[14]:

- Higher level of driver comfort
- Added margin of safety through extra maneuvering room
- Lessening of the impact from incidents on adjoining lanes

Buffers narrower than the prescribed 1.2 m (4 ft) minimum may be detrimental to safety in some cases. Where space constraints preclude incorporation of buffers of this width, double striping and access limitations may be employed in an effort to enhance lane separation, reduce merging and weaving conflicts, and allow for smoother HOV-lane operations. Some researchers assert that the traffic dynamics and design considerations of specific projects may cause buffer separation and limited ingress and egress treatments to be an advantage in some locations and a disadvantage in others[14].

Locating Access Points

Strategically locating access points in relation to freeway ramps and providing adequate weave distances and merge areas to mitigate the formation of crash "hot spots" are keys to providing safe access points on limited-access HOV facilities.

Studies in California have found that the primary safety impact of HOV facilities with buffers and limited access is the location and timing of congestion and crashes rather than the overall crash rate[11, 19, 20]. Crashes on limited-access buffer-separated facilities tend to be concentrated around ingress/egress points. Merging and weaving maneuvers are condensed to the vicinity of access points, causing a migration of congestion and crashes to these locations. Conversely, collisions on HOV lanes with continuous access are typically distributed more evenly along the length of the facility.

Barrier versus Buffer

A multi-year analysis of crashes on freeways in Dallas indicated that crash rates increased following the implementation of HOV lanes with narrow buffers. Crash rates on the I-35 East corridor rose by 56 percent from the pre-HOV period (1997) to after the implementation of an HOV lane with a 0.75 m (2.5 ft) buffer (2000). In the I-635 corridor, crash rates rose by 41 percent after the implementation of a concurrent HOV facility with a 0.9 m (3 ft) buffer. Little change in crash rates was observed following the implementation of a barrier-separated contraflow HOV lane in the I-30 corridor[10]. Project researchers indicated that barrier-separated HOV facilities are the preferred design where sufficient right-of-way capacity exists[21].

Some practitioners have identified positive safety impacts of non-separated designs, such as a reduction in driver confusion with respect to the operation of part-time HOV facilities. However, the absence of designated access points on these facilities may degrade overall safety between adjacent traffic flows by allowing weaving and merging to occur at potentially hazardous locations, and exposing motorists to the effects of speed differentials. Safety issues may also arise as a result of an increased incidence of non HOVs using the HOV lane as a passing lane or vehicles in the HOV lane using the inside general-purpose lane to pass slower-moving HOVs where conditions permit.

Although there is no consensus on whether the presence or absence of buffers and limited access has a systematic impact on facility safety, it is generally agreed that both buffer- and non-separated HOV lanes are less safe than barrier-separated designs.

Enforcement Sites for Non-Barrier-Separated HOV Facilities

The design and location of enforcement sites on concurrent HOV lanes is particularly difficult due to the relative ease with which violators can enter and exit the facility. Patrols and other enforcement agency personnel should be consulted in the design process to ensure that enforcement zones are suitable and safe.

If the provision of a continuous enforcement shoulder is not possible, designated enforcement areas should be considered at regular intervals. Enforcement shoulder widths of 3.6 to 4.3 m (12 to 14 ft) are necessary to safely identify, segregate, and ticket violators and allow them to safely reenter the traffic stream. HOV facilities offering more than one lane of travel per direction may require additional refuge/enforcement space, signage, and striping for safe operations.

If dedicated shoulder enforcement zones are utilized, they must also be of sufficient length. The minimum length required to safely pull over and cite violators on freeway HOV lanes and allow them to reenter the traffic stream is approximately 400 m (1,300 ft), excluding tapers. Additional safety features that should be considered to enhance enforcement safety and effectiveness include:

- Protective barriers for officers monitoring traffic
- Extra lighting at and around enforcement areas
- Median opening that allows officers to observe HOV-lane operations in both directions

Space constraints in arterial street environments result in fewer opportunities to implement special enforcement areas or treatments. In most cases, patrols will simply use available roadway, curb, or driveway space to conduct enforcement activities on arterial street HOV lanes.

Flexible Tubular Markers to Reduce Buffer Violations

Possible safety modifications to substandard buffer-separated HOV lanes include the use of 1 m (43 inch) flexible tubular markers inserted into a raised 2-inch channel between the striping of the buffer. Although the poles can be struck by vehicles if necessary, they represent a strong visual and psychological barrier to buffer violations. Use of 350 poles on a small portion of I-635 in Dallas has significantly reduced collisions involving unexpected maneuvers into and out of the HOV lane in the three years since their installation[18]. Plastic buffer posts have already been incorporated into the design of a future HOV facility in a constrained Dallas-area corridor.

In some jurisdictions, such as California, enforcement agencies have requested **shoulder widths** of 4.3 to 5.0 m (14 to 16 ft) to provide additional refuge space and to improve enforcement safety.

Buffer Separation with Tubular Markers

One of the largest applications of plastic poles on an HOV or HOT facility in the United States is the SR-91 Express Lanes in California. Approximately 10,000 tubular markers have been installed in the buffers separating the Express Lanes from general-purpose lanes (see Figure 4-9). The plastic markers or posts are spaced at 3.6 m (12 ft) intervals to facilitate maneuvers by emergency-response vehicles. According to the facility operator, a buffer and tubular marker design was used instead of fixed barriers due to lack of available right of way. A detailed analysis of the safety impact of this treatment has not been conducted, but crash data compiled by Caltrans and the California Highway Patrol (CHP) indicate that the SR-91 Express Lanes are comparable to other preferential facilities with respect to crash rates[22]. The drawback to tubular markers is the maintenance expenses associated with replacement. In the case of SR-91, 300-400 markers require replacement every three to four weeks.

Additional research is required to assess long-term safety and financial costs and benefits associated with this treatment.

Figure 4-12. Flexible Tubular Markers Used to Reduce Buffer Violations.

Speed Differential and Crash Rates

A 1988 study that examined freeway HOV-lane crashes and speed differentials in California found a positive relationship between the magnitude of the speed differential and crash rates on concurrent HOV facilities with minimal buffers (0 to 0.6 m [0 to 2 ft])[23].

Safety Considerations Involving Speed Differentials

Several HOV studies have found that the primary safety impact of using buffers and limited-access treatments on an HOV facility is the location of crashes, as opposed to the overall crash rate. The distinct crash patterns exhibited on buffer-separated HOV lanes with limited access is primarily due to the concentration of merging and weaving maneuvers at access points. Crashes on HOV lanes with continuous access are typically distributed more evenly along the length of the facility. However, the absence of designated access points on these facilities may degrade safety between adjacent traffic flows by increasing the exposure and vulnerability of motorists to the effects of speed differentials during weaving maneuvers.

Drivers on an HOV lane that is not physically separated from general-purpose traffic tend to voluntarily reduce their speed advantage over vehicles in adjoining lanes. This occurs for two reasons[15]:

- Motorists are uncomfortable with a large speed differential between their vehicles and vehicles just a few lateral feet away.

- Vehicles in the HOV lane must slow to match speeds with general-purpose traffic when exiting the HOV lane.

These "friction" related slowdowns are beneficial to the safety of concurrent HOV lanes. The reduction in speed differential between the HOV and adjacent lanes significantly decreases the likelihood of crashes during merge/diverge movements[15]. Large speed differentials between adjacent lanes create more dangerous merging conditions and increase the probability of a crash. Slower vehicles must merge into a high-speed HOV lane or faster vehicles in the HOV lane must rapidly decelerate in order to merge into the general-purpose lane. Either action may result in a sideswipe or rear-end crash[8].

A wide buffer does not physically prevent motorists from illegally entering or exiting an HOV lane. However, it may enhance safety by making it less likely that slow-moving vehicles in congested general-purpose lanes will suddenly veer into a fast-moving HOV lane or vice versa. Wide buffers also facilitate the provision of extended acceleration, deceleration, and weave lanes, which can enhance HOV safety by increasing storage capacity, reducing congestion at egress locations, smoothing merging activities at high-speed ingress points, and alleviating general access conflicts. Relatively few buffer-separated HOV facilities in the United States incorporate these treatments.

HOV facilities with **wider buffers** that are at least 3.0 m (10 ft) wide offer potential safety advantages over facilities with narrow buffers (less than 1.2 m [4 ft]). These include:

- Greater separation of traffic flows and reduced exposure to speed differentials and erratic maneuvers
- Improved driver comfort and incident isolation
- Illegal access/buffer violation more obvious
- Potential for incorporating wider and longer acceleration, deceleration, and weave lanes.

Wider Buffers

Two recently-constructed concurrent HOV lanes on I-84 and I-91 in Hartford, Connecticut have minimum left barrier offsets and a wide 4.2 m (14ft) buffer between the HOV lane and the general-purpose lanes. The extra-wide buffer is sufficient to safely accommodate disabled vehicles and enforcement activities (see Figure 4-13). Although no formal safety studies have been conducted, project stakeholders report that the most common safety challenges associated with these facilities are buffer violations and the reluctance of non-HOVs to allow HOVs to safety merge into the general-purpose lanes at egress locations[24].

Figure 4-13. Concurrent HOV Facility with a Wide Buffer[25].

Potential Negative Safety Impacts of Wide Buffers

A quantitative analysis of the safety impact of adopting a wide buffer design as opposed to a buffer-separated design with a wide left enforcement shoulder/refuge area and a standard 1.2 m (4 ft) buffer has not been undertaken and published. Potential negative safety impacts of wide buffers over long distances include:

- Use of the buffer as a breakdown or refuge area
- Use of the buffer for passing

The use of appropriate striping and pavement markings can help counteract these problems. For concurrent HOV facilities, medium to wide buffers are generally used in conjunction with limited access. Facilities with narrow buffers (1.2 m [4 ft] or less) may provide either limited or unlimited access. Table 4-16 compares some of the safety-related impacts of these access treatments.

Table 4-16. Safety-Related Impacts of Limited versus Unlimited Access (adapted from[14]).

Criterion	Buffers with Limited Access	Unlimited Access
Safety Impacts	• Concentrates merging and weaving at designated areas • Reduces merging between access points and where lane geometry or sight distances create hazardous conditions • Impact is location specific	• Reduces driver confusion for part-time HOV lanes • Queued general-purpose traffic can maneuver into HOV lane unexpectedly, creating perceived or real crash danger
Isolation from General-Purpose Congestion and Incidents	• Reduces impact in HOV lane from incidents and congestion in general-purpose lanes	• HOV volumes can spike at congestion hot spots as HOV traffic shifts into the HOV lanes
Impact on General-Purpose Traffic	• If designed well, weaving can be concentrated where adequate capacity exists • Direct access further reduces weaving to access HOV lane	• Weaving is distributed along an entire corridor • Concentrated weaving at inappropriate locations or inadequate weave distance exacerbates bottlenecks and safety issues

The context in which an access treatment is used and its potential effect on traffic flow and congestion patterns are important determinants of HOV-lane safety. Unlimited access treatments facilitate lane utilization for HOVs and non-HOVs for part-time facilities. Restrictive access treatments are more appropriate for full-time HOV facilities. The design and operation of interconnected HOV lanes and networks should remain consistent whenever possible as these factors affect driver expectancy and behavior. Local safety concerns may necessitate consideration or adoption of unique treatments.

Practitioner Safety Concerns for Buffer-Separated HOV Lanes

Responses to a 2003 Texas Transportation Institute survey of 23 transportation professionals with HOV-lane experience reflect the variability of local safety concerns encountered by practitioners. Respondents were asked to indicate their relative concern for a range of safety issues associated with buffer-separated HOV lanes. Compiled results of the ranking portion of the survey are shown in Table 4-17.

Table 4-17. Practitioner Safety Issues for Buffer-Separated HOV Lanes-Level of Concern[10].

Issue	High	Medium	Low	No	N/A	No Response	Total
Vehicles Illegally Crossing Buffer	6	5	3	1	5	3	23
Vehicle Merges at Ingress/Egress	3	5	5	1	5	4	23
Lack of or Reduced Inside Shoulder Width	5	6	5	0	2	5	23
Reduced HOV-Lane or Mainlane Widths	0	3	6	5	5	4	23
HOV Lane Used For Disabled Vehicles	4	1	5	5	4	4	23
HOV Lane Used For Evasive Action	3	5	6	1	4	5	23

Survey responses and written comments indicated that illegal buffer crossings were perceived to have a significant detrimental effect on facility safety. Safety concerns related to vehicles darting in and out of buffer-separated HOV lanes and the difficulty that carpools, vanpools, and buses have in anticipating and reacting to these maneuvers were highlighted.

Common Concurrent HOV-Lane Crash Scenarios

In the Dallas HOV-lane safety study, analysis revealed that crash rates increased following the introduction of buffer-separated HOV lanes. Several common crash scenarios involving vehicles in the HOV lane and the adjacent general-purpose lane (Lane 1) were identified. These included[10]:

- Vehicles in Lane 1 trying to avoid suddenly stopped general-purpose lane traffic by quickly moving into the HOV lane (evasive maneuver) are involved in a crash with a fast-moving HOV-lane vehicle
- Vehicles suddenly stopping in Lane 1 being rear ended by a following vehicle
- Vehicles suddenly moving from the HOV lane to Lane 1 being rear ended by another vehicle in Lane 1 that is unable to stop
- Illegal lane changes (i.e., crossing the double white line) from the HOV lane and Lane 1 at locations other than proper access points are causing both rear-end and sideswipe crashes
- Vehicles in highly congested Lane 1 attempting to move into the HOV lane while still traveling at low speeds are involved in a crash with a faster moving vehicle in the HOV lane
- Stopped traffic in the HOV lane due to a disabled vehicle (e.g., vehicle with flat tire) causes rear-end crashes because fast-moving vehicles in the HOV lane are not expecting to encounter the stopped traffic

The types of crashes observed on and around buffer-separated HOV lanes in Dallas have been noted on similar facilities throughout the country. Many of the crashes that occur on the buffer-separated HOV lane or the adjacent general-purpose lane are related to the substantial speed differential between the two lanes. Various studies have found that that high speed differentials and merging into and out of the HOV lane are significant causes of crashes. Incidents blocking HOV lanes have also been cited as a significant contributor to crashes[8]. Two studies in the late 1980s that assessed the safety of California's State Route-91 buffer-separated HOV lane and State Route-55 non-separated HOV lane found that the installation of HOV lanes resulted in a migration of crashes to downstream locations and a significant increase in rear-end collisions involving vehicles that were slowing or stopping. This was attributed the impact of the HOV lane on the location and timing of congestion and the effects of light trucks in reducing sight distances in heavy traffic conditions .

In 1992, a study on the relative safety of a non-separated HOV lane (SCL 101) in Santa Clara County, California, determined that the HOV facility contained more pronounced crash "hot spots" than non-HOV facilities. Large speed differentials and conflicts between traffic in the rapidly moving HOV lane and the stop-and-go general-purpose lanes were identified as primary safety concerns[11]. An evaluation of the buffer-separated portion of the El Monte Busway in California between July 1, 1999, and June 30, 2001, noted that approximately 80 percent of crashes on that facility were either rear-end or sideswipe collisions[26].

Weaving and Merging at Access Points

Other safety issues of concern are related to the difficulty of vehicle merges at designated ingress/egress locations. A vehicle in the HOV lane desiring to merge into the adjacent congested general-purpose lane may be unable to find an acceptable gap in general-purpose lane traffic. Difficulty merging may cause a motorist to slow down or stop in the buffer area or within the HOV lane, possibly blocking other HOV-lane traffic from continuing. Stopped traffic in the HOV lane is usually unexpected and may result in rear-end crashes. As discussed previously, speed differentials pose similar safety concerns for vehicles attempting to merge from slow-moving general-purpose lanes into a high-speed HOV lane. Potential design countermeasures to address weaving and merging problems, speed differentials, and related access safety issues are:

- Cross sections that allow merging vehicles to slow or stop when merging
- Provision of acceleration and deceleration lanes (where feasible) and access treatments that minimize weaving

Use of HOV Lane by Disabled Vehicles

Substandard inside shoulder width may cause disabled vehicles to stop on the HOV lane, either partially or completely blocking the lane. During uncongested time periods, drivers may unwittingly park a disabled vehicle on an operating HOV lane, endangering the safety of HOVs and travelers in adjacent lanes[10]. This problem can be especially prevalent if the HOV lane has been developed using the former inside shoulder of the general-purpose lanes and is separated by a buffer that resembles an edgeline. Design techniques that can be employed to counteract these safety problems include:

- Avoiding differences in pavement color or texture between the HOV lane and mainlanes that can contribute to driver confusion regarding the designation of the HOV lane.
- Properly signing and marking HOV lane at regular intervals along its entire length.

Using double solid or skipped lines to more forcefully delineate HOV facility (single line resembles edgeline and is less conspicuous).

Summary of Cross-Section Recommendations for Non-Barrier-Separated Facilities

Given the frequency and potential seriousness of these crash types, every effort must be made to ensure that HOV-facility designs incorporate features that help prevent them and the conditions that cause them. The following cross-section recommendations address these concerns:

- The minimum cross section for a buffer-separated HOV lane (illustrated in Figure 4-10), provides enough room for two 2.4 m (8 ft) wide vehicles to be side by side in the HOV-lane area (inside shoulder, HOV lane, and painted buffer) without encroaching on the general-purpose lanes. This is important because it allows two vehicles with a large speed differential to avoid a collision[10]. It should be noted that the AASHTO guidance recommends that this minimum cross section be used only on an interim basis or for short distances.

- Other HOV-lane design considerations such as strategic location of at-grade access points to minimize weaving conflicts and the formation of congestion can also be used to mitigate safety issues.

- The minimum cross section for non-separated HOV lanes (illustrated in Figure 4-11) does not allow for two vehicles to be side by side in the HOV area at the same time. Therefore, this design should only be used in exceptional cases, on an interim basis, and for short distances.

Queue Bypass HOV Lanes

Facility Description

Queue bypass or queue jump lanes are short HOV lanes that enable high-occupancy vehicles to circumvent congestion at specific locations such as freeway ramp meters. They may be used on a stand-alone basis, or as part of an integrated HOV-lane network. The design of queue bypass facilities varies considerably according to application. Figure 4-14 illustrates a common configuration of a freeway entrance ramp with a metered general-purpose lane and an HOV bypass lane.

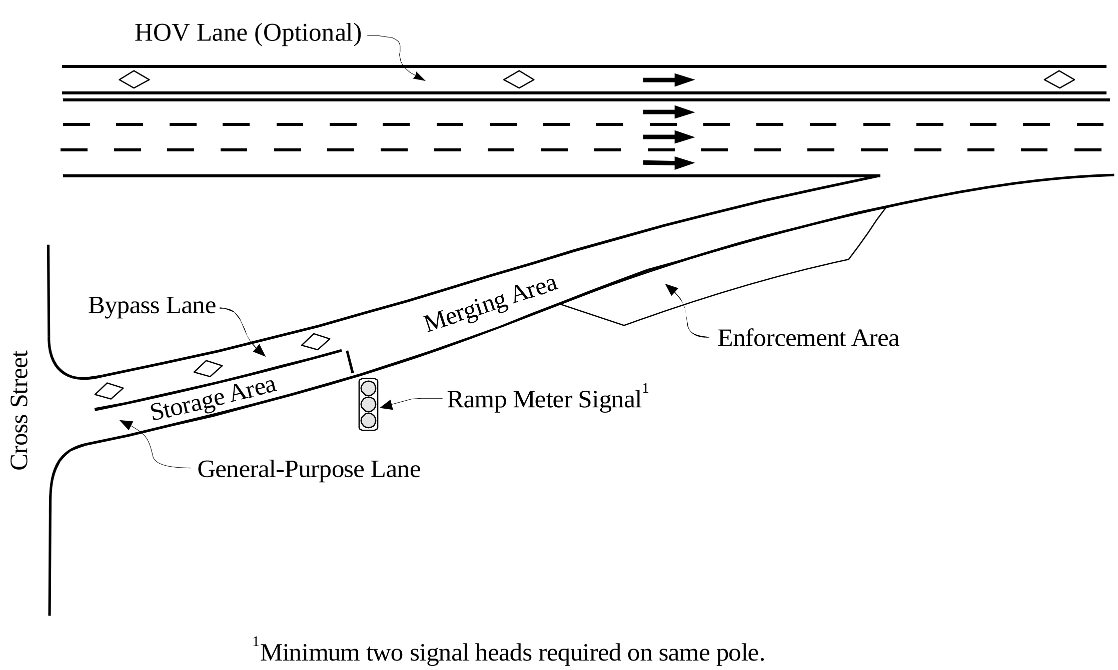


Figure 4-14. Queue Bypass HOV Facilities[6].

Left-Hand Location of Queue Bypass Facilities

Positioning of the bypass lane depends on ramp geometrics and other considerations. Locating the bypass lane to the left of the general-purpose lane has several safety advantages[6]:

- Permits HOVs to pass on the left
- Less likely for queue bypass to be blocked at the street entrance
- Offers HOVs a larger turning radius on loop ramps

However, the left-side location does have the safety disadvantage of requiring bus operators to merge to their right where the visibility tends to be restricted. The width of the bypass lane is governed by the type of operation, curvature, and the traffic volume and mix. Lane widths of 3.6 to 4.5 m (12 to 15 ft) are common[6]. Warning signs and traffic control devices should be used prior to and on the ramp to indicate when it is in operation and to prevent erratic maneuvers.

Additional Safety Considerations Associated with Facility Design

Limited research has been conducted on the safety impact of HOV queue bypass facilities. One of the most common types of treatments is the ramp meter bypass. HOVs typically move through the metering signal without stopping, while vehicles in the metered lane must stop and queue. These lanes taper into one lane prior to merging with the freeway lanes. The provision of a queue bypass preserves travel time savings and trip reliability for high-occupancy traffic. However, there are several potential safety concerns associated with this type of treatment (adapted from[27]):

- A violator (or HOV) that finds itself in the metered general-purpose lane may create a vehicle conflict by attempting to change lanes into the faster HOV lane.

- Where the bypass and metered lanes converge after the metering signal, there is the potential for merging-related crashes to occur.

- Vehicles entering a ramp with a queue bypass must immediately split into two lanes. The unpredictable maneuvers sometimes brought about by this design may create a safety problem.

- If the metered queue extends back onto the surface street, HOVs may attempt erratic maneuvers to bypass this temporary delay and move directly onto the ramp and into the queue bypass lane.

Safety-Related Design Recommendations

Consideration of safety issues in queue bypass design can prevent or alleviate some of the above-mentioned concerns:

- Incorporation of a raised median island between the general-purpose lane and the bypass lane imparts characteristics of an exclusive ramp to the bypass facility, improving safety by separating moving and stopped vehicles[6].

- If lane separation is not possible and the ramp has sufficient storage capacity, the HOV queue bypass should begin after the ramp entrance point. Though the single-lane ramp entrance may periodically delay HOVs, it should largely eliminate conflicts at ramp entrances[8].

- Proper signage, lighting, and pavement markings should be utilized to reduce erratic maneuvers prior to and on the ramp.

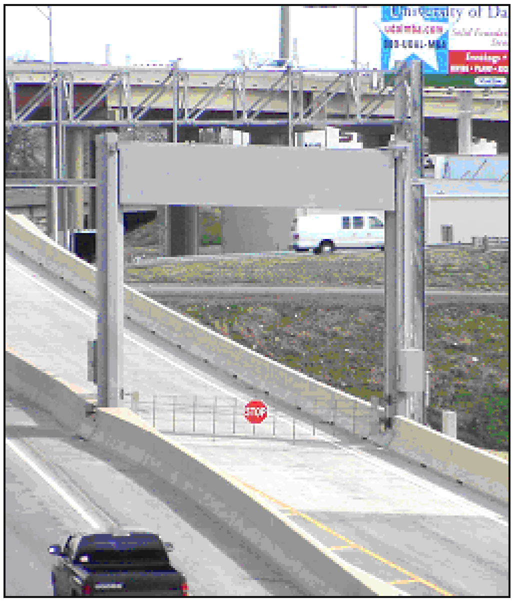
- Regular monitoring of metering rates, queue lengths, and HOV operations should be conducted to optimize the operation of the ramp and minimize unnecessary queue formation and traffic problems.

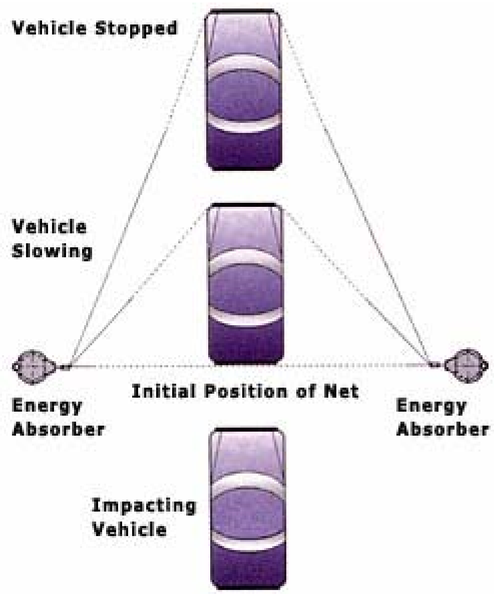
- Sufficient merging distance should be provided on the body of the ramp so that HOVs and general traffic can safely merge together and assume the same speeds prior to entering the freeway[8].

The design of the ramp meter bypass should be determined by safety considerations related to geometric, operational, and traffic demand conditions at each location. Consultation with local transit agencies, traffic engineering agencies, and traffic management center personnel is recommended when determining which side the HOV bypass will be located and whether or not the HOV bypass will be metered[28, 29, 30]. On curved ramps, the HOV lane should generally be on the outside of the general lane (i.e., the lane having the larger radius). This gives the non-stop HOVs a lower degree of curvature, but more importantly, metered lane traffic has a clearer rear view of the HOV lane, thus reducing the hazard of their changing lanes[8].

HOV Safety Design: Vehicle Arresting Barrier

Name – Vehicle-Arresting Barrier (VAB)





Safety Relevance – System prevents wrong-way movements and crashes on HOV facilities

Contact – Mahesh Kuimil, Dallas Area Rapid Transit (DART), Tel. (214) 749-2822

Location – Dallas, Texas	**Facility Type(s) –** Reversible barrier-separated HOV ramp
Safety Objective(s) – Prevent head-on collisions	**Project Date(s) –** System installed in 2001

Description

The Dragnet Vehicle Arresting Barrier is a safety system that can be used on reversible HOV lanes to prevent wrong-way movements and crashes. The barrier net, which is constructed of chain link steel and threaded by a continuous cable, is automatically raised and lowered from an overhead tower structure (see photo above). VABs are based on systems used to arrest aircraft on aircraft carriers. The net's cable is attached to energy-absorbing anchors that contain spools of metal tape. When the barrier is impacted by a vehicle, the tape is pulled through a series of offset pins. Deformation of the metal tape as is passes through these pins is the principal mechanism for absorbing the energy of the impact. This system has been installed and tested in various road applications including reversible lanes, railroad crossings, and drawbridges. It has few moving parts, requires minimal maintenance, and allows for smooth, safe deceleration of errant vehicles. The VAB installed on the reversible I-35E HOV facility in Dallas was manufactured by the Entwistle Company and cost approximately $300,000.

Safety Considerations

The Texas Department of Transportation (TxDOT), in conjunction with the Dallas Area Rapid Transit, proactively decided to incorporate the Dragnet Vehicle Arresting Barrier into the design of one of the city's reversible HOV-lane ramps where the potential existed for a severe wrong-way collision. The system is designed to ensure that motorists traveling at a high rate of speed on the adjacent freeway could not mistakenly enter the facility, penetrate existing ramp barricades, and collide with oncoming traffic. Although no impacts have been registered on the I-35E VAB since its installation in 2001, the system is designed to safely decelerate vehicles traveling at over 100 kilometers (60 miles) per hour with little danger to the occupants. In 2005, several additional VABs were installed at entrance ramps to reversible HOV facilities in Houston, Texas. Other operators of HOV lanes where the risk of wrong-way movements is high have also expressed interest in implementing this type of safety system to reduce fatalities, injuries, and litigation resulting from head-on HOV collisions.

CHAPTER FIVE
SAFETY CONSIDERATIONS IN HOV-FACILITY OPERATIONS

Introduction

This chapter focuses on safety considerations in HOV-lane operations. The chapter begins with an introduction to key entities involved in the operation of HOV lanes. Safety considerations pertaining to stakeholder activities are described and issues relevant to specific types of HOV facilities are examined. A model HOV-lane safety evaluation program is outlined to assist operators in identifying and mitigating safety problems. The case-study synopsis at the end of the chapter highlights safety and planning lessons learned from the introduction, demise, and subsequent reintroduction of Boston's I-93 contraflow HOV lane. The operational safety issues addressed in this chapter build on the planning and design considerations dealt with in previous chapters.

Section headings in this chapter:

- Stakeholders Involved in Safety-Related HOV-Lane Operations
- Safety Considerations in HOV-Lane Operations
- Model HOV-Lane Safety Evaluation Program for Operators
- Case Study: I-93 Contraflow HOV Lane – Boston, Massachusetts

Stakeholders Involved in Safety-Related HOV-Lane Operations

Safety is a key element of HOV-lane operations that affects the way in which project stakeholders carry out their responsibilities. Due to the nature of operational activities, the parties involved are primarily front-line personnel as opposed to planners or designers. The safety-related operational activities highlighted in this chapter are specific to HOV facilities.

<u>The State Department of Transportation</u> is often the lead agency responsible for operating freeway HOV facilities. Potential operational activities undertaken by state DOT personnel include opening and closing the facility, lane reversal, and facility maintenance and repair. The state DOT may also be responsible for facility surveillance and incident detection, though these activities may be jointly coordinated with local and regional agencies.

Transit Agencies operate buses on HOV lanes and can influence the safety of a facility through operational policies and practices such as the determination of bus headways and the reporting of incidents by bus drivers. In addition, transit agencies may provide HOV-lane policing, courtesy patrols and emergency tow-truck service.

State and Local Police enforce HOV-lane regulations and are typically the primary responders to incidents occurring on the facility.

Emergency Services provided by entities such as fire departments, emergency medical services (EMS), tow-truck operators, and hazardous materials contractors respond to incidents on HOV lanes. They attend to and evacuate vehicle occupants, extinguish vehicle fires, remove damaged or disabled vehicles, and clean up crash debris and hazardous-material spills. The manner and speed with which these services are provided affects facility safety.

Media involvement in HOV-lane safety centers on the communication of traffic incidents, delays, and alternate route information. Dissemination of this information by the media to motorists occurs via radio, e-mail messaging services, television, and other means. These services impact facility safety by reducing congestion and collisions in crash-prone locations or in areas where incidents or slowdowns already exist.

Table 5-1 provides a summary of the safety-related roles of stakeholders involved in HOV-lane operations.

Table 5-1. Safety-Related Roles of Stakeholders Involved in HOV-Lane Operations

Stakeholder	Safety-Related Activity
State Department of Transportation	• Open and close facility, reverse lane direction, provide maintenance and repair, surveillance/incident detection
Transit Agency	• Operate facility/transit service, may also provide policing and emergency tow service and surveillance/incident detection
State and Local Police	• Enforce HOV regulations, respond to incidents
Emergency Services – EMS, fire department, tow-truck operators, hazardous materials specialists	• Respond to and deal with incidents, evacuate injured personnel, remove damaged/disabled vehicles, clean up hazardous material spills
Media	• Communicate traffic incidents, delays, and alternate route information to motorists

Safety Considerations in HOV-Lane Operations

This section describes safety considerations associated with the operation of HOV facilities. HOV-lane guidance on the opening, closing, and reversal of facilities; incident management; and enforcement is presented.

Lane Opening, Closing, and Reversal

The general operational schedule of an HOV lane is often determined by facility type.

- Busways, barrier-separated two-way facilities, and buffer-separated concurrent facilities frequently operate on a 24-hour basis and do not need to be opened or closed. Non-separated concurrent HOV lanes that operate on a part-time basis automatically revert to general-purpose operation (no occupancy restrictions) during off-peak periods.

- While these facilities do not require opening or closing, their schedules may contribute to driver confusion and associated safety issues14.

- Contraflow and reversible barrier-separated lanes must be opened and closed on a daily basis. Traffic on these facilities must be reversed so that the lane operates in the direction of peak-period flow. Due to the potential for wrong-way movements and collisions involving operations crews, the way in which these operations are conducted has important safety implications.

For most contraflow and reversible HOV lanes, opening and closing the facility and reversing the flow of traffic entails the use of both manual and electronic procedures. Equipment employed in these operations to prevent safety incidents, wrong-way movements, and crashes includes:

- Barrier transfer machines or coning trucks
- Moveable barriers
- Posts, pylons, or drums
- Lane control devices
- Variable message signs
- Barricades, gates, and vertical swing arms

Manual placement/removal of safety cones, drums, or barricades at access points is often required to open and close reversible and contraflow HOV facilities. These devices are redundant safety treatments that should be used in conjunction with signage, beacons, gates, and barriers to prevent motorists from inadvertently attempting to access the facility when it is closed. The level of redundancy in access treatments and operations should correspond with the risk and potential consequences associated with inadvertent

The creation of an **HOV Facility Operating Manual** can provide safety advantages by documenting operation policies and procedures. The manual can provide a description of the HOV lane(s) and procedures for how the facility is to operate on a daily basis, offering guidance to operations, enforcement, and incident management personnel. From a safety perspective, an operating manual ensures that all important operational elements are covered and that all personnel have a uniform understanding of procedures.

access. Locations such as dedicated egress ramps, where wrong-way movements do not generally occur, present fewer safety-related operational issues than access sites such as high-speed ingress ramps.

Prior to opening an HOV facility, surveillance and incident detection technologies are utilized to identify disabled vehicles or other obstructions that may be blocking the lane. Traffic management center personnel monitor facility opening and closing procedures and should be authorized to prevent the HOV lane from opening if the facility cannot be safely operated.

- Moveable barriers, pylons, and tubular markers used on contraflow facilities should be deployed in the direction of the prevailing traffic.
- The removal of barriers or delineators is done in the opposite direction so that the lane reverts to normal use behind the crew.
- Variable message signs and traffic control signals should be controlled by or closely coordinated and verified with operations personnel on the ground to guard against equipment malfunction.

Reversible HOV Facilities

On reversible facilities, enforcement or operations personnel in a "sweeper" vehicle (usually a police cruiser or tow truck) physically open the lane. Beginning at the terminus of the closed facility, personnel in the sweeper vehicle travel in the opposite direction of intended lane operations. Access points are opened behind the vehicle as it proceeds toward the facility entrance. Safety-related operations associated with this activity include:

- Inspection/removal of lane obstructions/debris
- Verification of proper intelligent transportation systems (ITS) equipment function (lane control devices, variable message signs, warning beacons, automatic swing arms at park-and-ride lots)
- Removal and storage of barricades, cones where they will not be struck or dislodged
- Verification of proper manual gate function
- Securement of gates so that they do not impact passing vehicles (especially important at access points characterized by reduced lane widths and barrier offsets)

At the facility entrance, the sweeper vehicle may be parked in an unused portion of the reversible HOV ramp, outside of the lane of travel. The sweeper vehicle may be turned around within the lane so that it is facing the same direction as the prevailing traffic when the entrance to the facility is opened. Procedures for closing reversible HOV facilities are conducted in the opposite sequence. Figure 5-1 shows a number of operational safety treatments on a reversible HOV-lane park-and-ride ramp including cones, tubular markers for lane separation, vertical swing arms, and lane control devices. Barricades are stored off of the lane to the right.

Figure 5-1. Operational Safety Treatments on Reversible HOV-Lane Park-and-Ride Ramp.

Contraflow HOV Facilities

The operation of contraflow HOV facilities entails the deployment of moveable barriers, pylons, or flexible tubular markers along the entire length of the HOV facility. Where contraflow operations require manual placement of traffic control devices, special consideration should be given to the safety of operational personnel. This activity may expose operations crews to dangerous conditions. Inclement weather and darkness increase risks associated with these activities because personnel, vehicles, signage, and lane delineators become less visible. Redundancy in signage and procedures and special safety precautions should be incorporated into HOV-lane operations to reduce the potential for injury to operations personnel and motorists. As a result of safety concerns and technological advances, operations personnel on U.S. contraflow HOV lanes no longer walk alongside moving traffic streams to place and remove delineators.

However, some older contraflow HOV lanes do not utilize movable barrier systems because of geometric constraints and other limitations. The Lincoln Tunnel Exclusive Bus Lane in New Jersey is one such example. The facility relies on manual placement of tubular plastic post into pre-drilled holes in the pavement for lane delineation. A special "coning truck" was developed to enable personnel to place and retrieve the pylons while remaining on the vehicle. A police escort is provided to enhance the safety of this operation[31].

Contraflow Safety Precautions

Regardless of the level of technology used, certain safety precautions should be followed during the setup or removal of contraflow facilities:

- Barriers, pylons, or posts must be deployed in the same direction as prevailing traffic.
- Removal of these treatments occurs against the flow of traffic so that the lane reverts to normal use behind the crew.
- Operation of variable message signs and lane control signals is controlled by or coordinated with operations personnel during lane reversals.
- Safety training should be provided to all personnel deployed in the field for these operations.
- Appropriate safety equipment, such as fluorescent safety vests for operations personnel, should be provided.

More sophisticated technology has automated this process on other contraflow facilities. In Boston, Dallas, New York, and Honolulu, moveable concrete barriers are used to establish positive separation between the HOV and general-purpose traffic and to reduce the exposure of crews to potentially dangerous operational environments. A special "zipper" truck laterally transfers the hinged barriers into place, creating the HOV lane. Figure 5-2 shows the operation of this vehicle along a portion of H-1 in Honolulu, Hawaii. The safety implications of adopting this technology are further discussed in the case study at the end of this chapter.

Figure 5-2. Creation of a Barrier-Separated Contraflow Lane by a Zipper Truck[32]

Incident Management

The appropriate use of technology not only helps prevent HOV-lane crashes, it assists operators in planning for and dealing with incidents when they occur. Incident management is the coordinated use of personnel and resources to reduce the duration and impact of traffic incidents and improve the safety of motorists, crash victims, and responders. Incidents that can affect HOV-lane operations include:

- Crashes
- Disabled vehicles
- Adverse weather conditions
- Debris on the roadway
- Spilled loads
- Equipment or infrastructure malfunction

These events impact safety by creating lane closures, blockages and obstructions and potentially changing the type and volume of traffic using the HOV lane. Although incidents are generally considered random events, their occurrence and duration may be influenced by facility operations and design. Incidents on general-purpose lanes also have the potential to influence HOV-lane operations and safety. Figure 5-3 shows an incident on the outside general-purpose lane of an HOV corridor. Such events can result in the closure of the lane and the funneling of traffic into the remaining general-purpose lanes and the HOV lane. The reduction in capacity and maneuvering room caused by these events increases congestion and adversely affects safety.

Figure 5-3. Incident-Related Lane Closure in an HOV Corridor.

HOV-lane incident management procedures can differ among facilities and from those used on freeway mainlanes depending on the type of event. The following safety considerations pertain to incident management on major HOV facility types.

- Barrier-separated HOV lanes are generally isolated from mainlane incidents that impair operations on buffer and non-separated HOV lanes. However, barrier-separated facilities that do not provide sufficient room for drivers to safely maneuver around disabled vehicles within the facility complicate incident response and create additional safety problems.

- Incidents on non-barrier-separated HOV facilities that have a full inside shoulder are accessed and cleared more quickly than those on barrier-separated facilities with narrow shoulders.

- The lack of barrier separation and shoulders on arterial-street HOV lanes makes incident management practices on these facilities similar to those used on regular arterial-street lanes. These practices entail special safety precautions related to turning and parked vehicles and the interaction among modes and pedestrians.

The development and use of effective incident management strategies on HOV lanes enables initial events to be quickly addressed and secondary incidents to be prevented. Secondary incidents normally occur due to unexpected congestion and driving conditions surrounding the initial incident. It is estimated that the probability of a motorist being involved in a crash is 66 percent higher when an incident is already present[33].

The potential for a secondary event increases when unaffected motorists slow down to observe what has happened. This gawking or rubbernecking contributes to driver distraction and subsequent crashes, congestion, and delay. Secondary incidents are also caused by vehicles that overheat and become disabled while waiting for a primary incident to be cleared. This underscores the importance of developing HOV incident management plans that enable incidents to be dealt with safely and expeditiously. Preventing civilians, tow-truck drivers, police officers, and other incident responders from being struck by passing vehicles should be the foremost objective. The following section describes the four steps in incident management and their implications for HOV-lane safety.

1. Incident Detection

Incident detection and verification is the process of identifying information about the nature of an incident, the number of vehicles involved, and where and when it occurred. Rapid incident detection enables subsequent management elements to be initiated in a timely manner. This reduces secondary incidents and improves the operational safety of the facility. Detection information must be sufficiently detailed to dispatch the appropriate responders to the scene of the incident. Various methods and technologies can be used to collect and verify information about HOV-lane incidents. These include:

- Closed circuit television (CCTV) cameras viewed by Traffic Management Center personnel
- Automatic vehicle identification systems
- Other electronic traffic measuring systems such as inductive loop systems, radar and algorithms that detect traffic abnormalities
- Emergency motorist aid telephones and call boxes
- Radio communications with bus drivers
- Radio communications with police or roaming service patrols

- Aerial surveillance
- Cellular telephone calls from motorists
- DOT or public works crews reporting via two-way radio
- Private traffic reporting services

2. Communication with Motorists

Communicating information about an incident to motorists can relieve congestion upstream of the incident and improve motorist safety. This is achieved through a variety of means, such as:

- Commercial radio broadcasts
- Highway advisory radio (HAR)
- Variable message signs
- Email and text messaging alert services
- Television traffic reports

Incident reporting and communication should begin immediately after the event is detected, occur throughout the response, and continue until the incident has been cleared and normal traffic flow has resumed. Dissemination of this information to motorists allows efficient rerouting of traffic around the incident. In practice, motorists are often not promptly notified of the resumption of regular traffic flow following an incident. Failure to communicate incident resolution to motorists may result in needless rerouting of traffic and the creation of congestion and safety issues on alternate routes.

3. Incident Response

Incidents pose a danger to motorists on HOV and general-purpose lanes because they reduce roadway capacity and contribute to congestion, delays, and secondary incidents. A general guideline is that congestion behind an incident takes three to four minutes to return to normal for each minute of delay[6]. Thus, rapid incident response is critical to managing congestion and minimizing the safety impact of these events. The first stakeholder to detect or become informed about an incident is not usually the one that responds to it. Coordinating an appropriate and safe incident response requires advanced planning and training by individual agencies and stakeholders as well as collective groups. Incident response training exercises should be conducted to test multi-stakeholder incident response plans. Table 5-2 presents potential stakeholders response strategies for common HOV-lane incidents.

Table 5-2. Potential Incident Response Stakeholders and Strategies[6].

Incident	Potential Response Strategies
Disabled vehicle (flat tire, run out of gas, etc.)	• Commercial towing service • Police
Disabled bus	• Transit operator tow truck and replacement bus • Commercial towing services • Police to manage traffic
Crash/no injuries	• Police • Commercial towing service
Crash/injuries	• Emergency medical services (EMS), ambulance • Police • Commercial towing service
Crash/special problems (toxic substance, etc.) or hazardous waste	• Police • Commercial towing service • Fire, EMS, or other special response team
Facility damage and/or debris	• Emergency maintenance repairs
Snow, ice, flooding, or other weather-related emergency	• Snow plows and other service vehicles • Commercial towing service

Site management and traffic management duties are crucial safety-related activities that are undertaken by incident responders. Site management entails the organization and coordination of personnel and equipment at the scene of the incident to protect responders, victims, and motorists. Primary site management responsibilities are:

- Assessment of incident
- Prioritization of activities
- Notification of appropriate stakeholders
- Clear communications

The establishment of a formal incident command system allows responding agencies to coordinate their efforts without having to negotiate authority and develop response plans on scene or for each individual incident. Pre-planned incident response strategies improve coordination and reduce response time and the potential for secondary events. On-site incident management activities should be complemented by the use of traffic management tools including lane closures, ramp metering, traffic signal adjustments, and designation of detours.

4. Incident Clearance

Incident clearance involves various activities including:

- Removal of disabled vehicles, wreckage, and debris from the roadway
- Clearance of pedestrians and parked vehicles from the incident scene
- Return of the facility to normal operations

Due to the narrow lane width of contraflow facilities, stalled vehicles must either be pushed to the end of the lane or removed by tow truck. If towing is required, the tow vehicle must generally approach the disabled vehicle from the opposing direction. Drivers of emergency aid vehicles that may have to use this maneuver to reach vehicles in the contraflow lane should be adequately trained[8].

Severe incidents that result in infrastructure or equipment damage may require repair before the HOV facility can be safely reopened. General safety precautions used by operational personnel in the opening, closing, and reversal of HOV facilities should also be adhered to during the clearance of incidents. Police officers, firefighters, EMS personnel, and tow-truck drivers should receive proper safety training and equipment prior to responding to HOV-lane incidents. VMS and other methods of communication should be fully leveraged to promptly advise and update motorists regarding the location and status of the incident.

Enforcement

Enforcement is an essential component of HOV-lane operations. The presence of stationary and roving patrols on an HOV facility helps ensure that vehicle-occupancy and eligibility requirements are adhered to and that the lane operates as intended. Insufficient enforcement can result in higher violation rates, reduced travel-time savings, and decreased travel-time reliability for legitimate users. The potential safety implications of inadequate HOV-lane enforcement include congestion-related conflicts and crashes causes by excess demand and problems related to illegal maneuvers. Conversely, too much enforcement can also be detrimental to safety.

Some facility operators report that the use of multiple officers to **patrol HOV-lane enforcement sites** exacerbates gawking and congestion and creates congestion and additional safety concerns. Light but consistent enforcement appears to be an effective approach for reducing HOV violations and related safety incidents.

General Enforcement Strategies

Depending on the availability of resources and agency priorities, a single enforcement technique or a combination of enforcement approaches may be utilized. Potential enforcement strategies include stationary patrols, roving patrols, team patrols, and multipurpose patrols. The appropriate type, location, and level of HOV-lane enforcement also depends on the HOV facility in question. Enforcement strategies often differ for concurrent and barrier-separated facilities:

- Concurrent buffer-separated and non-separated HOV lanes should be designed with a continuous enforcement shoulder where possible so that violators can be safely pulled over by roving patrols and issued citations anywhere along their length. Enforcement of these facilities sometimes involves a coordinated effort by team patrols in which violators are identified at an observation point and apprehended by stationary or roving patrols at a downstream location. Roving patrols may also monitor vehicle occupancies and eligibility while patrolling the HOV lane or adjacent mainlanes. Where adequate space and a safe environment for enforcement are provided, stationary patrols can be located.

- Barrier-separated HOV lanes facilitate enforcement because violators are prevented from entering and exiting the facility at will. This type of HOV lane is normally enforced at or near access locations where traffic speeds are lower and off-peak lane capacity may be utilized to improve the safety and effectiveness of enforcement activities. These dedicated sites may be operated by stationary patrols on a regular or selective basis.

Occupancy Determination and Officer Safety

Among the safety issues associated with HOV-lane enforcement, preventing officer injury is the foremost consideration. Because an automated method of accurately determining the number of human beings in a moving vehicle has yet to be developed, officers must manually count the number of occupants in each vehicle. The safety of this task is influenced by operational practices and the planning and design considerations discussed in previous chapters.

Vehicle-occupancy verification is most effective when conducted by officers on foot. Enforcement personnel standing at the roadside have a clearer vantage point of the interior of passing vehicles and can better control the speed of vehicles than officers sitting inside of a patrol car. This reduces viewing obstructions and enables more accurate determination of vehicle occupancies. The following types of vehicles present particular challenges with respect to occupancy determination or verification:

- Panel vans
- Vehicles with tinted windows
- Vehicles carrying babies or small children
- Vehicles with children or adults lying down on a seat
- Vehicles with empty child seats
- Elevated pick-up trucks and sport-utility vehicles

Conditions such as darkness, sunlight glare and reflections, rain, fog, or snow can also complicate occupancy determination. The need for officers to position themselves at the roadside next to moving traffic creates a potentially dangerous enforcement environment. In order to reduce the exposure of officers to injury, vehicle speeds in active enforcement zones should be reduced through the use of variable message signs, beacons, or other traffic control devices.

Devices used to alert drivers to the presence of enforcement personnel on foot should be directed at HOV-lane traffic only. These warnings can be especially helpful in improving the safety of enforcement activities conducted during periods of darkness.

Safe enforcement activities….

- Incorporate use of reflective vests to enhance the visibility of enforcement officers in low-light conditions.
- Avoid use of flashing police lights or other indiscriminant warning devices that distract drivers in adjacent lanes.
- Avoid use of enforcement beacons which tend to cause drivers to abruptly or illegally exit the HOV lane in an attempt to avoid enforcement.
- Include positioning of enforcement vehicles in visible locations, outside of the lane of travel, and parked so that they can protect officers from errant vehicles (see Figure 5-4).

Figure 5-4. Enforcement Site at a Reversible HOV-Lane Entrance.

Data Collection

Data collection is an important component of HOV-lane operations. It enables facility operators and other stakeholders to gauge the success of the facility and identify weaknesses. Safety issues associated with the collection of HOV-lane data are similar to those encountered by enforcement personnel. Vehicle-occupancy data collection can be especially dangerous in freeway settings where speeds are high and the presence of data collectors may be unexpected. The following issues should be addressed to enhance the safety of data-collection initiatives:

- Authorization to collect data on an HOV lane should be obtained from the facility operator and local/state law enforcement authorities.
- Input from facility operators, enforcement personnel, transportation officials, consultants, researchers, or others that have undertaken similar efforts should be solicited to identify the safest and most convenient data-collection sites.
- Orientation and training sessions that include thorough reviews of data-collection sites, safety procedures and precautions, provision of safety vests and other equipment, and trial data-collection sessions should be mandatory prior to data-collection activities.
- Coordinate data-collection efforts with HOV-lane enforcement activities so that data collectors can take advantage of protected sites and slower traffic at enforcement locations.
- Freeway vehicle-occupancy data should be collected from inside a marked vehicle such as a van to minimize the possibility of injury and to improve viewing vantage points.
- The data-collection vehicle should be parked safely outside of the lane of travel, in a clearly visible location.

Model HOV-lane Safety Evaluation Program for Operators

Evaluating the safety of an HOV lane is a process that has traditionally been undertaken by the operating agency or a project stakeholder following development of the facility. The HOV-lane performance monitoring process entails the collection and analysis of "before" and "after" safety data and the reporting of results. This process may be augmented by independent safety assessments called road safety audits (RSAs). The following section describes techniques employed in crash data analyses and road safety audits.

Crash Data Analysis

An analysis of injury crash rates before and after the implementation of an HOV facility provides a means of measuring changes in crash potential relative to exposure in vehicle-kilometers traveled or vehicle-miles traveled. Several years of crash data must be compiled at the corridor and lane level to undertake this type of evaluation. Due to reporting issues, only injury-related crashes (as opposed to property-damage crashes) are used as a safety metric. Injury crash rates are typically expressed per million or 100 million VKT or, more commonly in the United States, VMT.

The ability to determine injury crash rates and compare safety performance is contingent upon the collection of valid data. Chapter 3 describes performance monitoring tasks related to the identification of appropriate safety measures of effectiveness and the collection of related data. Information contained in police crash reports is the primary source of information used in crash data analysis. This information is electronically coded into a database by state personnel so that it can be manipulated and disseminated. Analysis and reduction of crash data enable analysts and researchers to determine whether a corridor experienced overall changes in crash occurrences from the years preceding HOV-lane implementation to the years following it. The impact of HOV lanes varies according to specific project considerations. Some HOV lanes are less safe than adjacent mainlanes and have negatively impacted corridor safety. In other cases, the implementation of an HOV lane has had a negligible or positive effect on corridor safety.

In order to better understand crash characteristics and ascertain their relationship to HOV-lane design and operations, a microscopic examination of crash locations and types is undertaken. This process entails a review of individual crash reports containing collision diagrams and other information that is not coded into electronic records. Common crash types associated with HOV-lane operations include rear-end and sideswipe crashes. Such collisions frequently occur at or near ingress/egress areas. Fixed object and run-off-the-road crashes also occur regularly on HOV lanes. Determination of the causes of these crashes involves assessment of a number of potential contributing factors such as:

- Congestion
- Speed differentials
- Weather/pavement condition
- View obstruction
- Speeding (or going too slow)
- Illegal maneuvers
- Facility type, design
- Construction activity
- Enforcement activity
- Incidents
- Other driver behavior and environmental considerations

Analysis of these factors and associated crash data enables operators to detect statistical changes in crash rates for a corridor. It also permits the identification of crash patterns and safety trends brought about by HOV-lane implementation. However, conclusions with respect to overall facility safety must be statistically significant and should not be drawn on the basis of limited data samples. Determination of the safety impact of an HOV facility requires multi-year data-collection and analysis that accounts for crashes on the HOV lane and all other lanes and shoulders in the corridor.

Provided adequate data collection has been planned for and undertaken, crash reports and data can typically be used to calculate crash rates before and after HOV lane implementation. In addition, crash data can be plotted by location (milepoint) to determine the areas where a significant number of collisions are occurring. If there is a significant difference in the pattern of crashes before and after the HOV lane opened, these differences may be attributed to the HOV lane. The geometric and operational characteristics of the HOV lane may provide insight into high-crash locations.

Crash Data Analysis

Table 5-3 shows an example of injury and fatality related crash rates before and after a concurrent buffer-separated HOV lane was constructed in the northbound direction of Interstate-35 E in Dallas, Texas.

Table 5-3. Before and After Crash Rate Comparison for an HOV Corridor[34].

IH-35E North with Concurrent Flow Buffer-Separated HOV Lanes From IH-635 to Dallas Co. Line (Cont. Sect.: 0196-03 From Milepoint 28.5 to 34.5)									
Injury- and Fatality-Related Crashes									
Year	Total Crashes	Peak Period	EB/WB	Non-serious/ Serious	Weekday/ Weekend	Mainlane/ HOV	Veh.-Miles Traveled (100 Mil VMT)	Crash Rate (Crashes/ 100 Mil VMT)	Peak Period Crash Rate
90	74	-	38/36	69/5	54/20	74/na	2.57	29	-
91	75	-	40/35	67/8	50/25	75/na	2.55	29	-
92	64	-	35/29	52/12	53/11	64/na	2.64	24	-
93	104	37	57/47	95/9	70/34	104/na	2.64	39	45
94	110	35	61/49	94/16	78/32	110/na	2.7	40	53
Construction of HOV Lanes (3)									
97	157 (Const.)	-	85/72	150/7	117/40	154/3	2.98	53	-
98	162	54	87/74	145/17	119/43	157/5	3.49	46	67
99	162	65	85/77	155/7	123/39	158/4	3.43	47	78

Notes:

(1) Nonserious = possible or non-incompacitating injury, Serious = incompacitating injury or fatality.

(2) Yearly Corridor VMT calculation for 1997-1999 includes HOV lane vehicles.

(3) HOV Lane Construction began 6/95 and ended 9/96.

A review of locations for individual crashes in the before and after conditions indicates increased crashes related to the northbound intermediate access location for the HOV lane between IH-635 and Valley View Lane (see Figure 5-5). The analysis of such data enables researchers and practitioners to identify trends in crash rates and make inferences about the safety of facilities and treatments at specific locations. Methods for evaluating the safety of transportation facilities (including HOV corridors and lanes), and identifying and ranking candidate locations for safety improvements, vary widely.

The federally-mandated Highway Safety Improvement Program (HSIP) requires each state to "develop and implement, on a continuing basis, a highway safety improvement program which has the overall objective of reducing the number and severity of crashes and decreasing the potential for crashes on all highways[35]." Highway HOV facilities are encompassed within these programs.

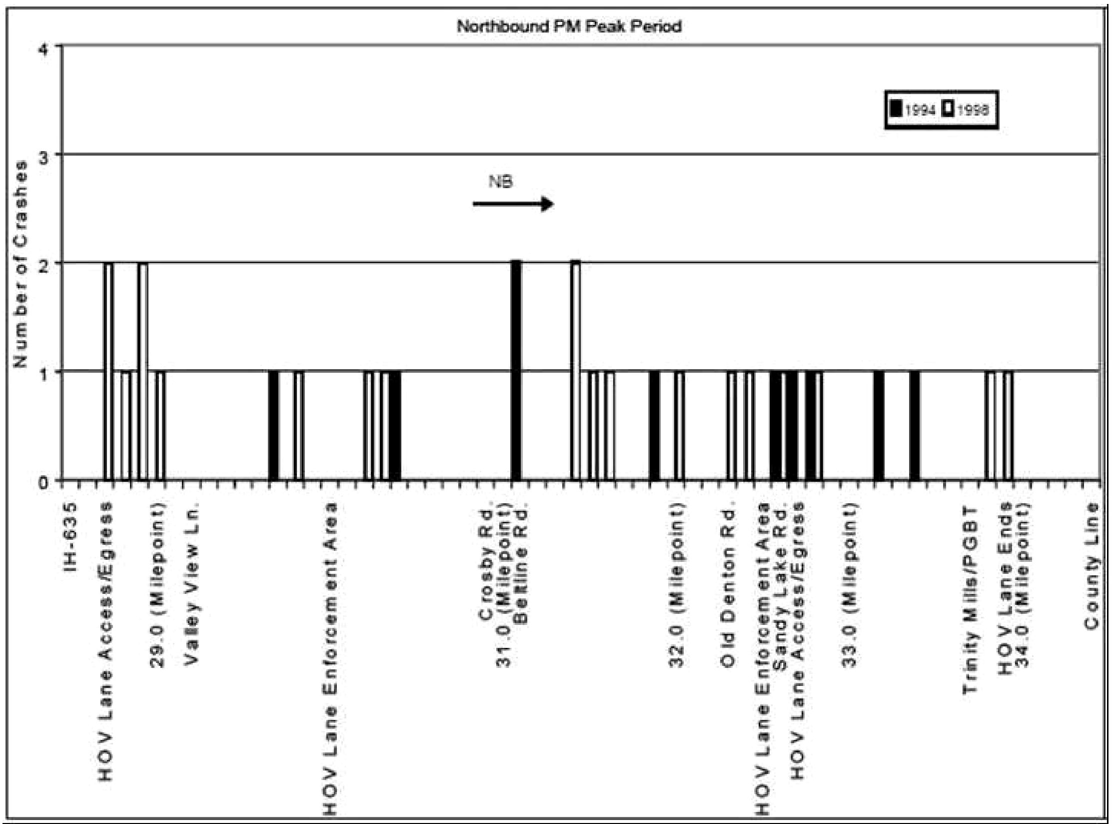


Figure 5-5. Before and After Fatality and Injury Crash Data Comparison by Location for an HOV Corridor[34]Error! Bookmark not defined..

Whether part of a broader initiative or not, a model HOV-safety evaluation program should incorporate the three components outlined below[36].

Planning

The planning component dictates which safety improvements are implemented and evaluated, and consists of the following steps[36]:

1. Collect and maintain data (including crash, traffic, and roadway data),
2. Identify hazardous locations and elements,
3. Conduct engineering studies, and
4. Establish project priorities (i.e., utilize some type of benefit/cost analysis).

Safety planning activities are typically conducted over a period of several years and culminate in the implementation of safety improvement projects

Implementation

The implementation process follows closely from the last two steps in the planning component where specific projects are assessed with respect to their feasibility (including whether they meet required benefit/cost targets) and priority[37]. Projects that are subsequently designed and constructed must then be evaluated.

Evaluation

Evaluating the impact of recently-implemented highway projects is critical to determining their effectiveness and advancing future safety improvement efforts. The evaluation process consist of a feedback loop in which data on post-construction safety performance is gathered, problems are identified and ranked, and additional improvements or countermeasures are developed.

Road Safety Audits

The road safety audit is a model that can provide HOV-lane operators with an additional analysis technique for facility safety prior to, during, or after facility construction. RSAs are formal examinations that are conducted to identify potential safety risks associated with the facility and ensure that measures to eliminate or reduce them are fully considered by the project management team. Safety is enhanced by recognizing and addressing crash-producing elements in the planning, design, or operational stages of a project and mitigating remaining risks that cannot be eliminated. Key RSA objectives include:

- Minimize the frequency and severity and cost of preventable collisions
- Minimize negative safety impacts beyond the project limits (i.e., avoid inadvertently increasing collision risk elsewhere on the road network)
- Consider the safety of all road users, including vulnerable road users such as Bicyclists
- Reduce the need for post-construction remedial works to address safety issues

The flexibility of the RSA process enables this safety evaluation technique to be applied to road transportation projects of any type or size, and in any phase of development. The RSA is conducted by a qualified team of specialists that possess road safety engineering, traffic engineering, and geometric design expertise. Various possible distinctions exist between traditional safety evaluation activities conducted by planners and designers, and RSAs (which are usually conducted by independent road safety auditors). Table 5-3 summarizes some of these potential differences.

Table 5-4. Comparison of Traditional Safety Reviews and Road Safety Audits[38].

Traditional Safety Reviews	Road Safety Audits
Safety reviews generally use small (1-2 person) teams with design expertise.	A safety audit uses a larger (3-5 person) interdisciplinary team.
Safety review team members are usually involved in the design.	Safety audit team members are usually independent of the project.
Field reviews are usually not part of safety reviews.	The field review is a necessary component of the safety audit.
Safety reviews concentrate on evaluating designs based on compliance with standards.	Safety audits use checklists and field reviews to examine all design features.
Safety reviews do not normally consider human factors issues. This includes driver error, visibility issues, etc.	Safety audits are comprehensive and attempt to consider all factors that may contribute to a crash.
Safety reviews focus on the needs of roadway users.	Safety audits consider the needs of pedestrians, cyclists, emergency vehicles, and heavy trucks, as well as traditional users.
The safety review is reactive. Hazardous locations are identified through analysis of crash statistics or observations and corrective actions are taken.	Safety audits are proactive. They look at locations prior to the development of crash patterns to correct hazards before they happen.

The six steps that comprise road safety audits are outlined below[39]:

1. Start-up meeting:
   - Meeting between the design team, project owner, and safety audit team
   - Exchange information, provide drawings, background reports, establish schedule, communication protocols
2. Site Visit:
   - Safety audit team visits site to gain an understanding of project parameters and identify potential safety issues
3. Audit Analysis:
   - Safety audit team reviews the background materials and the proposed/existing design and identifies potential safety issues for road users
4. Audit Report:
   - Safety audit team prepares a detailed report documenting the safety issues and suggests potential solutions to the problems at a conceptual level
5. Findings (Completion) Meeting:
   - Safety audit team meets with design team and project owner to discuss the safety audit findings

- Provides opportunity for design team and project owner to clarify any safety issues

6. Response (Exception) Report:
   - Design team and/or project owner provides a written report documenting the actions taken by the design team or project owner for each safety issue raised in the audit report
   - For recommendations that are rejected, reasoning should be provided

For further information about RSAs including an extensive checklist of items commonly reviewed by RSA teams, the reader is encourage to consult the National Cooperative Highway Research Program's *Synthesis 336: Road Safety Audits*[43].

Road Safety Audits (RSAs)

The experiences of RSAs in Australia, the United Kingdom, Denmark, and elsewhere have quantified the safety and economic benefits of implementing this process[40]. Canadian authorities report that the costs of RSAs for capital projects exceeding $10 million are typically less than 0.5 to 1 percent of the project cost depending on the stages required and the complexity and scope of project[41]. The use of RSAs on U.S. road infrastructure projects is a relatively recent phenomenon, though some states have developed considerable experience over the past decade. The Pennsylvania DOT, for example, has commissioned dozens of small-scale safety audits on non-HOV projects at a cost of $2,000 to $8,000 per audit. This investment has reportedly resulted in numerous safety improvements, such as interchange reconfigurations, intersection realignments, fixed object removal, traffic control and delineation improvements, and protected roadside areas for enforcement agencies[42].

HOV Safety Operations: I-93 Contraflow HOV Lane

Name – I-93 Contraflow HOV Lane

Safety Relevance – Lessons learned/implemented to improve safety of contraflow HOV-lane operations

Contact – Paul Jodoin, Massachusetts Highway Department, Tel. (617) 973-8817

Location – Boston, Massachusetts	**Facility Type(s) –** Contraflow barrier-separated HOV lane
Safety Objective(s) – Safe contraflow lane setup, operation, and removal	**Project Date(s) –** 1971 initial contraflow buffer-separated HOV lane, 1977 concurrent HOV lane, 1995-present contraflow barrier-separated operations

Description

Two of the three HOV facilities that have been implemented on Boston's I-93 Southeast Expressway over the years have been contraflow facilities. Initially, exclusive bus lanes were established in which the inside off-peak lane was converted to peak-direction use during the morning and afternoon rush hours. These lanes were separated from opposing traffic flows with plastic cones that were manually placed and retrieved. The project was halted shortly after its inauguration when one of the workers was struck and killed while setting up cones. The safety risks inherent in manual cone placement and retrieval, combined with potential dangers associated with contraflow operations in the absence of barrier separation, were the primary reasons for the failure of the project. In 1977 an effort to establish concurrent HOV lanes on the Southeast Expressway was aborted after less than two weeks of operation due to poor project planning and communications which resulted in the "empty lane" syndrome and intense public opposition to the project. In 1995, contraflow HOV lanes were again implemented on the Southeast Expressway. Greater emphasis on safe operational procedures and treatments on this facility has contributed to its success.

Safety Considerations

The Massachusetts Highway Department incorporated several safety-related operational and design considerations into the most recent contraflow HOV facility on the Southeast Expressway. Separation of HOV traffic from opposing traffic flows is achieved through the use of a moveable barrier system developed by Barrier Systems Incorporated. A special "zipper" truck (see photo above) laterally transfers the hinged barrier 4.3 m (14 ft) across the inside off-peak lane, creating an additional peak direction lane. This renders manual cone placement and retrieval unnecessary and protects HOV traffic from errant vehicles in the general-purpose lanes (and vice versa). Facility safety is further enhanced by leveraging ITS technologies such as CCTV, mobile and fixed VMS signs, and remote technologies to more closely monitor operations on the 9.7 kilometer (6 mile) facility and improve incident detection, communication and response. The barrier-separated contraflow lane is safer to enforce and the collection of HOV-lane data has been made easier and safer through the provision of a special control center located at the facility.

CHAPTER SIX
SAFETY CONSIDERATIONS IN THE DEVELOPMENT OF HOT FACILITIES

Introduction

This chapter addresses unique safety-related issues associated with High-Occupancy Toll (HOT) facilities. The intent of this chapter is not to replicate general guidance related to HOT-facility development, but to highlight considerations that are relevant to safety. The issues addressed in this chapter supplement the HOV-lane safety information presented in previous chapters. Enforcement and driver-related safety concerns arising from special vehicle-occupancy determination techniques and tolling practices are examined. The case study at the end of the chapter assesses the safety benefits of the occupancy "self-declare" lane on California's State Route-91.

Section headings in this chapter:

- Description of HOT Concept and Operations
- HOT-Facility Safety Considerations
- Case Study: SR-91 Self-Declare Lane – Anaheim, California

Description of HOT Concept and Operations

Four of the five HOT facilities currently operating in the United States offer free access to vehicles with three or more occupants. Two facilities also allow two-person vehicles at no charge, while two others allow buy in for two-person vehicles but not for single-occupant vehicles.

The use of pricing and occupancy restrictions to regulate demand on HOT facilities permits more precise control over the volume of vehicles using the facility. Data on average vehicle occupancies in the corridor, the magnitude of congestion and delays, and commuters' willingness to pay for faster and more reliable transportation options are used by planners to establish appropriate occupancy guidelines and pricing levels. Variable-message signs and other advanced technologies are used to communicate this information in real time to motorists in the corridor. By adjusting the toll levied on paying customers, facility operators can raise or lower demand and optimize lane utilization without significantly impacting the level of service. HOVs may utilize HOT facilities for free or at a discounted rate, depending on facility regulations and the number of occupants in the vehicle. Revenue generated from HOT-facility tolls is generally used to support facility operations or transit services.

What Are HOT Facilities?

HOT facilities are essentially HOV lanes that allow drivers of vehicles that do not meet occupancy requirements to purchase access. Like HOV lanes, HOT facilities are designed to improve person-movement and provide reliable, free-flow traffic conditions to facility users. They offer free or priority status to transit and carpools, while promoting more efficient use of space by selling excess capacity to users that would otherwise be denied access. All tolls are paid electronically and the toll rate varies according to the level of traffic on the facility to prevent congestion. Through the combined use of vehicle-occupancy regulations and electronic tolling, vehicle and person throughput are increased and a high level of service is maintained.

HOT-facility operation can be complex. They require that tolls be paid electronically with transponders instead of manually at toll plazas. Sophisticated traffic information and electronic toll collection systems are used to accomplish this task at freeway speeds. The number of access points on HOT facilities is often restricted to facilitate the management of traffic flows and maintain a high level of service. To prevent ineligible users from illegally entering and exiting the lanes, HOT facilities are separated from adjacent general-purpose lanes by concrete barriers or flexible plastic posts. The lone exception is the new I-394 Express Lanes project in Minneapolis that began operations in May 2005. Approximately two-thirds of this facility is delineated by double white striping (see Figure 6-1). The remaining one-third of the facility is barrier separated.

Figure 6-1. I-394 Express Lanes HOT Facility in Minneapolis.

HOT-Facility Safety Considerations

Most HOT facilities are developed through the conversion of existing HOV lanes, though new facilities are currently being planned. The process of planning, designing, and operating these facilities should incorporate the considerations highlighted in this handbook for HOV facilities; however, it also entails potential safety considerations beyond those indicated for HOV lanes. This section addresses the following unique safety issues associated with HOT facilities:

- Enforcement officer distraction
- Driver confusion

Enforcement Officer Distraction

HOT-facility enforcement can be more involved than HOV-lane enforcement. In addition to determining the number of occupants traveling in vehicles, officers may be required to verify the presence and validity of toll transponders. While technology facilitates this task, potential safety issues may arise.

Enforcement techniques vary according to facility configuration, operations, eligibility requirements, and technology. The SR-91 Express Lanes in California require that all vehicles with three or more occupants pass through a designated "self-declare" lane in order to receive a discounted toll rate. On other HOT facilities, enforcement personnel monitor vehicle-occupancy and transponder validity for all users. Fixed transponder readers and portable antennas, such as the vehicle-mounted devices employed by HOT-lane enforcement patrols in Minnesota, are used to identify vehicles that have operable and properly displayed toll transponders. As vehicles pass through the antenna read zone, a light or signal indicates whether a valid transponder is detected. If SOVs are prohibited from buying in to the facility, vehicles must be screened by enforcement personnel to ensure they are carrying a sufficient number of occupants. Likewise, if a valid transponder is not read, officers must count heads to determine whether the vehicle qualifies for free use of the facility.

Conducting the abovementioned HOT enforcement activities at high speeds is often difficult and dangerous. Verification of transponder existence/validity and vehicle occupancy can lead to officer distraction and increase the potential for vehicle-pedestrian collisions. The safety impact of tasking officers with multiple verification responsibilities can be mitigated in a number of ways. These include:

- Proper enforcement site design
- Appropriate signage
- Reduced enforcement zone speed limits
- Use of advanced toll transponder verification technologies

Depending on vehicle speed, congestion, time of day, weather conditions, and other factors, transponder signals can be difficult to read and match to passing vehicles. Handheld transponder readers can provide a convenient and effective method of verifying the signal of fixed-site transponder beacons without requiring officers to approach the traffic stream and endanger their safety. Vehicle-mounted transponder readers have been developed for use by roving patrols on the new I-394 Express Lanes HOT Facility in Minneapolis, Minnesota. Although these devices enable officers to identify violators while patrolling the lane, the degree to which they may contribute to distraction-related safety issues on the part of enforcement personnel is yet unknown. As with HOV enforcement personnel, HOT officers should receive proper safety training and equipment prior to deployment in the field.

Driver Confusion

The driving environment on HOT facilities is generally more sophisticated than that of other roadways. Motorists with no previous HOT-facility experience can become confused by various facility aspects such as:

- Eligibility and occupancy rules
- Toll transponder requirements
- Complex signage

Driver confusion and unfamiliarity with HOT-facility protocols can result in erratic maneuvers that endanger the safety of the driver, other motorists, and enforcement officers.

A unique feature of HOT-facility operations is the ability of the motorist to reduce the toll through carpooling. This typically entails affixing a toll transponder on the inside of the windshield if a specified occupancy threshold is not met. The transponder allows an appropriate fee to be deducted from its owner's account. If vehicle-occupancy requirements for free use of the facility are satisfied, the transponder must be removed from the windshield to prevent the account from being charged. Quickly reconciling vehicle-occupancy and tolling protocols and ensuring that the transponder is properly disengaged or stored is a process not encountered on general-purpose lanes or standard toll facilities.

Drivers that transport varying numbers of passengers in their vehicles sometimes forget to display or remove their transponders prior to entering the HOT facility. In an attempt to avoid fines or unnecessary toll charges, these motorists may scramble to display or store their transponders as they pass through the enforcement zone. These practices can compromise HOT-facility safety and endanger enforcement personnel standing in close proximity to the traffic stream. Drivers that mistakenly begin to enter HOT facilities occasionally make sudden, erratic maneuvers in an attempt to divert out prior to an enforcement zone. Methods of reducing driver confusion and dangerous maneuvers on HOT facilities include:

- Clear, concise signage in advance of facility access points helps reduce driver confusion regarding lane treatment, occupancy requirements, and pricing.
- Public outreach and marketing campaigns apprise motorists of facility regulations and operation, and common safety issues.

HOT SAFETY : SR-91 SELF-DECLARE LANE

Name – SR-91 Self-Declare Lane

Safety Relevance – Self-declare lane reduces enforcement safety risks and complexity

Contact – Herve Le Caignec, Cofiroute USA, Tel. (949) 754 01 98

Location – Anaheim, California	**Facility Type(s) –** Concurrent buffer-separated HOT facility
Safety Objective(s) – Simple, safe facility enforcement	**Project Date(s) –** HOT facilities opened in 1995

Description

The SR-91 Express Lanes project was the first high-occupancy toll facility in the United States. It was constructed in the median of State Route-91, a congested freeway connecting employment centers in Orange County, California, with residential areas in nearby Riverside County. The 10-mile express facility is comprised of two lanes in each direction with no intermediate access points. Separation from adjacent general-purpose lanes is achieved with flexible tubular markers that serve as a physical buffer. All vehicles using the facility must have an operable transponder and valid account for electronic toll payment. Toll prices are communicated to motorists via variable message signs at the entrance to the facility. Prices vary according to the time of day, level of congestion on the facility, and number of occupants in the vehicle. Vehicles with one or two occupants are changed the full toll. Vehicles carrying three or more occupants are eligible for a 50 percent discount. To receive the discount, HOV3+ vehicles must self-segregate into a designated lane (see photo above). The vehicle's license plate is automatically photographed so that if a valid transponder is not registered the owner can be mailed a citation.

Safety Considerations

The self-declare tolling format used on the SR-91 Express Lanes places the onus on HOVs to identify themselves. This lessens the complexity and safety issues associated with occupancy enforcement by reducing weaving and decreasing the potential for vehicle-officer conflicts at tolling/enforcement zones. Other HOT facilities that have attempted to force all paying customers to merge into special toll lanes have encountered safety and compliance problems. Rather than monitor the number of people in every vehicle on the facility, SR-91 enforcement officers are able to concentrate on verifying vehicle occupancies in the HOV3+ lane only. In addition to the safety advantages of this setup, facility operators benefit from reduced manual enforcement requirements and related cost savings. Notwithstanding these safety and operations benefits, self-declare lanes require additional right-of-way and may not be appropriate for facilities that have multiple access points or prohibit single-occupant vehicles.

CHAPTER SEVEN
FUTURE RESEARCH

Introduction

HOV and HOT-facility safety has received increasing attention in recent years. Nonetheless, there are many issues that have not been adequately addressed and require further study. The relationship between safety performance of a facility and the numerous variables that can affect it is not well understood. Data and information required to draw conclusions regarding causative factors are not available or have not been collected in many cases. Practices and techniques used to analyze and address HOV and HOT-facility safety issues are sometimes incomplete or out of date. The objective of this chapter is to raise awareness of outstanding safety issues by highlighting various needs, gaps, and opportunities related to HOV and HOT safety research.

The following research needs are discussed in this chapter:

- Improved HOV-Lane Crash Reporting and Analysis Techniques
- Countermeasures to Address Common HOV-Lane Safety Issues
- Use of Surrogates to Identify HOV-Lane Safety Deficiencies
- Safety Impact of Opening HOV Lanes to General-Purpose Traffic During Mainlane Incidents
- Safety Impact of Opening HOV Lanes to General-Purpose Traffic During Nights and Weekends
- Safety Impact of Allowing Heavy Trucks on HOV Lanes
- Human Factors in HOV and HOT-Lane Design and Safety
- Safety Implications of HOV Resentment Among Drivers in Mainlanes
- Use of Shoulder Rumble Strips to Mitigate HOV/HOT-Facility Crashes
- Use of Glare Screens to Reduce Driver Distraction and Safety Issues

HOV and HOT-Facility Safety Research needs

Improved HOV-Lane Crash Reporting and Analysis Techniques

Traffic safety problems can be identified and evaluated in an accurate and timely manner only through the systematic collection and maintenance of crash data[44]. The value of HOV-lane crash data can be compromised by deficient data-collection, reporting and analysis techniques. Crash reports prepared by law enforcement personnel constitute the principal source of information used to populate crash databases. Each state has its own standardized report form, which is completed by filling in dozens of blanks or multiple choice bubbles and preparing diagrams and comments that describe crash characteristics. The lack of a checkbox, bubble, or other crash report indicator denoting that a crash was HOV related obliges analysts in many jurisdictions to use more tedious methods of identifying and retrieving these records. These typically involve inputting milepost values and information on the number of lanes in the segment of the freeway where the crash took place.

A simpler means of distinguishing HOV and HOT-related collisions on crash reports and in database systems would facilitate the identification and analysis of these collisions. Creation of HOV- and HOT-specific line items within crash-archiving systems would enable pertinent crash records to be quickly filtered and shared with other jurisdictions for more meaningful safety analysis. Beginning in 1988, the Washington State Department of Transportation included a code on the crash data entry form to indicate whether a collision occurred in an HOV lane. An evaluation of the benefits of this indicator and its potential applicability to other jurisdictions is needed.

In addition to developing and disseminating improved means of identifying HOV and HOT-lane collisions, opportunities exist to incorporate more valuable safety information into crash reports. For example, crash databases often lack sufficient detail on the geometrics of facilities to enable proper safety analysis. Methods for improving communication and coordination between personnel that analyze crash information and those that collect it would enable safety data to be used more productively. Finally, there is a need to examine ways of enhancing the consistency of crash-data analysis procedures. Crashes occurring on general-purpose lanes are sometimes directly related to adjacent preferential facilities. Development of standardized procedures for the identification and analysis of these collisions would provide a more accurate view of the safety of these facilities.

Countermeasures to Address Common HOV-Lane Safety Issues

One of the challenges of integrating safety into HOV-lane design is the relative scarcity of research into HOV-lane safety problems and potential countermeasures. For example, merging and weaving at access points has been identified as a common element in many HOV-lane crashes. Various alternatives, such as limiting access to strategically-located points; separating ingress and egress; incorporating acceleration, deceleration and weave lanes; and providing unlimited access have been proposed and implemented to reduce crash rates at access locations. Further research is required to quantify the safety effect of adopting these access treatments in specific contexts.

A related cause of crashes on HOV lanes is congestion, which results in mainlane slowdowns and the development of dangerous speed differentials between HOV and general-purpose traffic flows. Most collisions that occur during congested conditions are rear-end crashes. The remaining are often sideswipes, possibly resulting from drivers attempting to avoid rear-end collisions. Remedies such as ramp metering and variable posted speeds have had limited success in addressing these problems. There is a need to intensify research in this area, and to develop and test additional countermeasures. Designing concurrent HOV lanes with a narrow inside barrier offset and a wide (at least 3.6m [12 ft]) buffer/breakdown area between the HOV lane and the general-purpose lanes is a design alternative worthy of further study. The use of plastic tubular markers to improve lane delineation and reduce buffer violations and encroachment on facilities built in constrained rights-of-way is another design treatment of considerable interest.

Use of Surrogates to Identify HOV-Lane Safety Deficiencies

The use of advanced crash study techniques and technologies enables researchers, analysts, and practitioners to better understand the causes of collisions on HOV lanes. They also provide a tool for identifying crash-prone locations and developing and evaluating remedies. But there are limitations to the use of crash data for estimating the safety of HOV facilities.

Crash statistics only indicate the failure of drivers, vehicles and roadway elements to function together as intended. They do not account for the potentially larger number of events that result in near misses or possible conflicts. The relative magnitude of actual crashes to safety-related events on a given roadway is illustrated in Figure 7-1. If a crash does not result in an injury or property damage over a specified amount ($1,000 in many states) it may not be reported by law enforcement. In some cases, motorists are reluctant to report crashes for fear of increasing their insurance rates[45]. Crash reports may also contain erroneous information or lack necessary elements for valid safety analysis. Mistakes related to distance estimates at crash scenes are common, as are errors introduced when crash reports are coded.

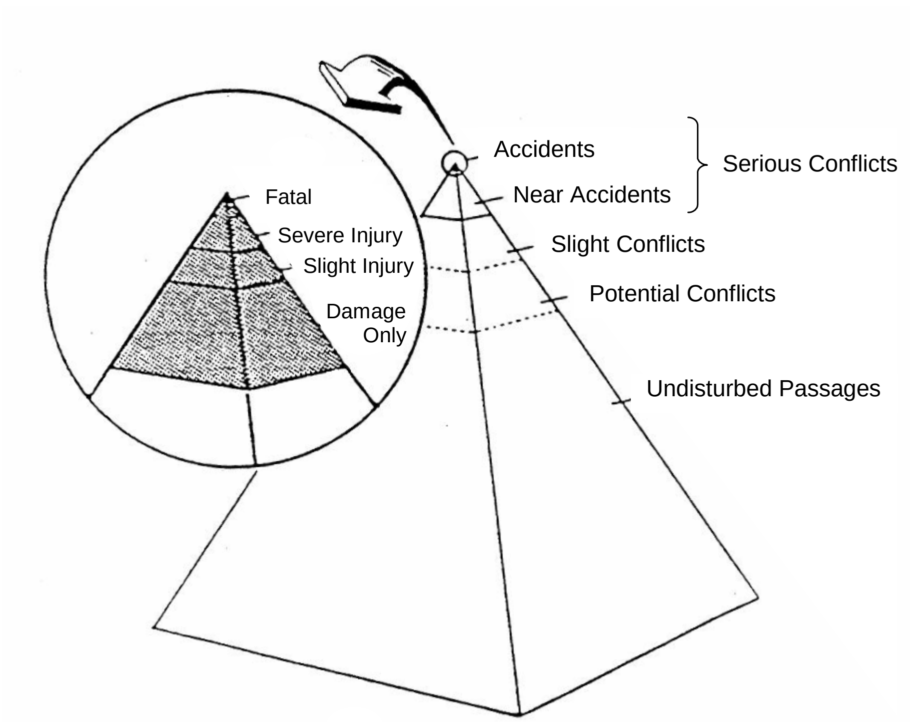


Figure 7-1. Relative Magnitude of Safety-Related Events on a Roadway[46].

These problems have prompted the development of alternative measures of safety, called surrogates. Surrogates do not depend on crash data. They are useful for identifying potentially unsafe conditions that result in frequent near misses. One surrogate that has proven to be an effective proxy for safety is the time-to-collision (TTC) analysis method. When used in the micro-simulation environment, TTC helps determine the time that it would take for one vehicle to collide with another vehicle if they were to continue at the same speed without taking evasive action[47]. In the context of HOV operations, this method would involve video surveillance of potentially dangerous sections of the facility where vehicles might collide, such as access points. Given that video monitoring of HOV facilities and congested corridors is already widely accepted for traffic and incident management purposes, potential privacy issues associated with this safety analysis technique may be minimized. The use of surrogates should be examined as an additional HOV-lane safety research tool to supplement crash data analysis techniques and proactive approaches such as road safety audits.

Safety Impact of Opening HOV Lanes to General-Purpose Traffic during Mainlane Incidents

Incidents on general-purpose lanes often result in the closure of one or more additional lanes so that responders have a safe area in which to work. HOV lanes that are not blocked due to the incident may be opened to general-purpose traffic for congestion-relief purposes. Most jurisdictions and facility operators do not have formal policies with respect to the opening of HOV lanes during incidents. Decisions may be made on a case-by-case basis by the facility's operations supervisor or through consultation among operations, enforcement, and traffic management personnel.

Where formalized guidelines do exist for opening HOV lanes to general-purpose traffic during incidents, they vary by jurisdiction. Factors such as the number of mainlanes blocked or the duration of the blockage are sometimes considered. The Virginia Department of Transportation opens HOV lanes to general-purpose vehicles when traffic is blocked for more than 10 minutes. The Dallas Area Rapid Transit authority opens its HOV facilities to mixed traffic whenever multiple mainlanes are blocked by incidents[48]. In California, Caltrans and the California Highway Patrol (CHP) jointly decide whether to permit non-eligible vehicles on HOV facilities following major multi-lane incidents[49]. This approach has also been used in Houston, where heavy flooding and major collisions have occasionally caused the Texas Department of Transportation and Metropolitan Transit Authority of Harris County (METRO) to open HOV lanes to all traffic[16]. Table 7-1 summarizes these approaches.

Table 7-1. Selected Criteria for Opening HOV Lanes to Mixed Traffic During Mainlane Incidents.

Lead Agency	Criteria for Opening HOV to Mixed Traffic
Virginia DOT	Mainlane traffic blocked for 10 minutes
Dallas Area Rapid Transit	Multiple mainlanes blocked
Caltrans/CHP	Consultation between Caltrans and CHP
TxDOT/METRO	Consultation between TxDOT and METRO

The safety implications of opening HOV lanes to general-purpose traffic during mainlane incidents have not been extensively studied and are not well understood. Safety in the HOV lane may be jeopardized by increased traffic levels, a sudden influx of drivers unfamiliar with HOV-lane operations, or vehicles that are incompatible with facility design. The possible creation of an "incident island" surrounded by lanes of moving traffic can be extremely hazardous and may exacerbate safety problems for incident responders if the HOV lane remains operational and is opened to mixed traffic. Once the incident has been addressed, it may be difficult and dangerous to close the HOV lane to general-purpose traffic. Research is necessary to determine the net safety impact of temporarily converting HOV lanes to general-purpose lanes during mainlane incidents. Safety considerations could be studied in conjunction with the numerous equity issues surrounding this topic.

Safety Impact of Opening HOV Lanes to General-Purpose Traffic During Nights and Weekends

Some HOV lanes are underutilized or closed during off-peak periods such as nights and weekends. Increasing traffic volumes and slower speeds have been noted at these times on many adjacent general-purpose lanes. Opportunities may exist to increase utilization of HOV facilities during nights and weekends by temporarily suspending occupancy restrictions and opening them up to general-purpose traffic. The objective of this operational change would be to reduce congestion in the mainlanes without unduly affecting the safety or performance of the HOV facility.

A 2002 HOV study undertaken in Seattle, Washington, recommended that a number of HOV lanes in that region be opened to general-purpose traffic between 7 PM and 5 AM. Prior to adoption of the recommendation, the Washington State Department of Transportation completed a number of safety improvements on the HOV lanes to mitigate safety impacts. These included the installation of left-hand rumble strips, the provision of increased clear zones, and the addition of guardrails[27]. Evaluation of the safety impact of allowing single-occupant vehicles on HOV lanes at night (including an analysis of before-and-after crash data, crash-prone locations, and the frequency and severity of crashes) is currently ongoing. Additional research is necessary to assess the safety implications of adopting similar policies in other regions.

Safety Impact of Allowing Heavy Trucks on HOV Lanes

The use of HOV lanes by heavy trucks is a concept that has yet to be thoroughly tested or examined. Currently, heavy trucks are restricted from virtually all HOV facilities in the United States, with the exception of the I-95/395 and Dulles Toll Road HOV lanes in Virginia. Legislation in that state permits heavy trucks to drive on HOV lanes on interstate highways that have more than two lanes in each direction, provided occupancy requirements are met. Other jurisdictions have indicated an interest in examining the use of heavy trucks on HOV lanes during all or a portion of their operating period. This would likely reduce truck traffic on general-purpose lanes and may decrease the number of conflicts and collisions between heavy trucks and passenger vehicles. However, such a measure would require public acceptance, approval from facility sponsors, and extensive safety planning and analysis.

The unique characteristics of heavy trucks (including their weight, dimensions, acceleration and deceleration characteristics, and turning radii) could require design, maintenance, and operational considerations that diverge significantly from those of existing HOV facilities. The potential for increased crash severity as a result of the mixing of passenger vehicles and heavy trucks on HOV lanes poses additional concerns. Other potential safety-related issues include degradation of facility performance and responder access, sight-distance deficiencies, enforcement difficulties, and conflicts with supporting facilities such as direct ramps. Further research is needed to understand the net safety impact of allowing heavy trucks on HOV lanes. This research should include an analysis of the distinct design and operational characteristics of different classes of heavy trucks expected to use HOV facilities.

Human Factors in HOV and HOT-Lane Design and Safety

Many HOV and HOT facilities are characterized by complex driving environments that oblige motorists to process information quickly. The decision to use an HOV facility may involve consideration of hours of operation, vehicle eligibility, occupancy requirements and other factors. HOT-lane utilization can include additional considerations related to price, transponder placement, lane selection (depending on vehicle occupancy), and other issues. Decisions and actions associated with these considerations are often performed while traveling at a high rate of speed and undertaking maneuvers such as lane changes. Given the relative complexity of driving on preferential facilities and the potential for driver confusion and distraction, clear signage, enforcement setups, and facility design is essential.

Optimization of HOV and HOT-facility design and operations reduces human errors and enhances safety. Interactive driving simulators provide a valuable tool for studying and improving facility design and operations based on human reactions. This technology can be programmed to replicate existing or potential driving environments to determine the safest and most effective characteristics and practices. Considerable potential exists to leverage human factors research and driving simulator technology to advance the safety of preferential facilities

Safety Implications of HOV Resentment Among Drivers in Mainlanes

Preferential facilities can impart substantial travel time and reliability benefits to users. These benefits generate feelings of resentment on the part of some non-HOVs, particularly among drivers that do not use these facilities and do not support the HOV or HOT concepts. A slow-moving single-occupant vehicle on a congested mainlane may be reluctant to yield to the user of a preferential facility that has been traveling in free-flow conditions and wishes to merge into the mainlanes. This attitude is most prevalent during periods of extreme congestion, where few natural openings in mainlane traffic exist. Feelings of frustration, resentment and related aggressive driving practices among some mainlane drivers often make it more difficult for users of HOV and HOT lanes to safely merge with general-purpose traffic at egress points. This contributes to sideswipe and rear-end crashes at egress sites. Evidence of this phenomenon comes primarily from crash victims and enforcement personnel and is largely anecdotal. Feelings of frustration also contribute to erratic maneuvers in which mailnlane drivers trapped in congestion suddenly veer into the HOV lane, causing a collision with a faster-moving vehicle. Formal investigation is needed to better define and quantify these safety issues and assist in the identification of appropriate mitigation strategies.

Use of Shoulder Rumble Strips to Mitigate HOV/HOT-Facility Crashes

Run-off-the-road crashes can be severe due to the high rate of speed at which vehicles are normally traveling at the time of impact. Motorists on HOV lanes are more susceptible to run-off-the-road collisions because they are often traveling in a lane at edge of the roadway. On retrofit projects, HOV facilities may be implemented in constrained environments that result in geometric design compromises such as narrow shoulders. Safety devices including barriers, guardrails, and energy-absorbing devices are frequently used to reduce the severity of run-off-the-road crashes on HOV lanes. The use of shoulder rumble (see Figure 7-2[50]) strips may also enhance the safety performance of these facilities.

Figure 7-2. Milled Rumble Strips.

Studies examining the impact of rumble strips in freeway environments have demonstrated their effectiveness in addressing run-off-the-road crashes. Several HOV lanes in the Seattle area have recently been retrofitted with shoulder rumble strips to mitigate potential safety issues associated with the opening of these facilities to general-purpose traffic during nights and on weekends. Further examination of the safety benefits and consequences of using milled or raised rumble strips on HOV and HOT facilities is required. Questions regarding their impact on crash rates, types, and severity should be addressed. Additional topics of investigation might include HOV/HOT-lane rumble-strip effectiveness by time of day, weather conditions, and vehicle class; and whether the introduction of shoulder rumble strips on select HOV/HOT facilities in a region increases crash rates on other facilities where this treatment is not applied.

Use of Glare Screens to Reduce Driver Distraction and Safety Issues

The installation of glare screens on concrete barriers has the potential to reduce both glare and driver distraction. Where traffic streams on a freeway are not separated by barriers with glare screens, the potential exists for motorists traveling on one portion of the facility to be distracted by events occurring on another. Crashes, enforcement activities, disabled vehicles, and other events draw attention away from the driving task and increase the risk of a crash. Glare screens may also prevent congestion from arising on HOV or HOT facilities due to speed differentials and voluntary slowing. By blocking the view of taillights in the general-purpose lanes, glare screens can reduce the tendency of drivers on barrier-separated facilities to slow down unnecessarily. This treatment is currently being considered on barrier-separated HOV facilities in northern Virginia due to excessive rubbernecking and unwarranted slowdowns. Potential safety drawbacks associated with the use of glare screens include a reduction of sight distances around curves and at other areas. Additional research is required to fully assess the safety impacts of adopting glare screens on HOV/HOT facilities and to define appropriate deployment strategies.

Safety Considerations in HOV/HOT-Facility Occupancy Enforcement and Data Collection

The enforcement of HOV-lane occupancy regulations and the collection of violation data can be difficult and dangerous. In order to count the number of persons in a vehicle, officers must position themselves in close proximity to the traffic stream. Standing next to moving vehicles involves inherent safety risks that demand careful attention on the part of enforcement personnel and drivers. Enforcement-area designs and procedures also affect the safety of these activities. Given that an automated solution for determining the number of human beings in a moving vehicle is not currently available, manual occupancy enforcement and data collection is required on all HOV and HOT facilities. Further investigation of the safest and most effective designs and practices for conducting these activities is required. The research should involve procedures applicable to a range of facility types and designs and include an assessment of techniques and scenarios both in the field and in controlled test track environments.

Speeding and HOV/HOT-Facility Safety

HOV and HOT facilities are designed to provide reliable and expedited travel options to multi-person vehicles in congested corridors. Facilities that offer high levels of service often enable drivers to travel at speeds well above the posted speed limit, especially through reduced speed zones. Regular facility users may consistently exceed legal speed limits in the absence of enforcement and meaningful penalties. Some facilities are not designed to safely accommodate vehicles traveling at excessive speeds, especially through access points and on curves and ramps. Drivers that become frustrated with motorists traveling at or slightly below the posted speed limit may engage in aggressive maneuvers such as tailgating, flashing of high-beam headlights or other unsafe driving practices. Further research examining the relationship between speed limits, enforcement, and driver behavior and HOV/HOT-lane safety is needed.

Figure 7-3. Mobile Speed Warning Trailer.

Safety Performance of Radial versus Circumferential HOV/HOT Facilities

HOV and HOT facilities can be implemented in radial corridors that branch out from a central business district or on circumferential beltways or other non-radial roadways. Regardless of the type of facility that is selected, its safety performance may be affected by considerations related to its location on a radial or circumferential route. Radial corridors are often characterized by unequal traffic distribution patterns caused by large numbers of commuters traveling inbound to a central business district or activity center in the morning and returning in the afternoon. This may create excessive peak-period demand and associated safety concerns.

Circumferential HOV lanes typically exhibit smoother traffic patterns but may be affected by other safety-related considerations such as trip type. Motorists using circumferential HOV and HOT facilities often make short trips that require numerous access points. This generates turbulence within the traffic stream, which can result in increased crash potential. Conversely, HOV and HOT facilities implemented on radial freeways are often line-haul facilities that serve longer-distance trips. They are characterized by fewer access points and less weaving to and from the HOV lane. Additional research is required to determine the safety impact of these corridor considerations on the overall safety performance of HOV and HOT facilities.

Safety Implications of Allowing Bicycles on HOV Lanes

The use of bicycles as a travel mode achieves many of the same objectives as carpooling or taking the bus. Bicycles represent a cost-effective travel option that reduces transportation-related fuel consumption and pollution and may alleviate traffic congestion. Currently, bicycles are permitted on several arterial-street HOV facilities in the Untied States. However, a comprehensive assessment of safety issues associated with bicycle use of arterial and freeway HOV lanes has yet to be undertaken.

Various factors contribute to the lack of safety knowledge regarding bicycle use of HOV lanes. Studies indicate that crash statistics significantly underestimate bicycle collision and injury rates. This is due in part to the scarcity of reliable trip data for the bicycle mode. In addition, collisions involving bicycles are often less costly than motor-vehicle crashes and may not be reported to the police or insurance companies. Unless hospitalization is required, injuries stemming from bicycle crashes may also go unreported. Although bicycles are generally viewed as incompatible with freeway HOV-facility design, a detailed study of bicycle use on freeway HOV lanes has not been conducted. An examination of the feasibility, requirements, and safety implications of allowing bicycles on freeway HOV lanes should be undertaken.

Safety Considerations for HOT Facilities in Extreme Winter Conditions

Until 2005, the only HOT facilities in the United States were located in southern California and southern Texas. The relatively mild winter climates at these locations create few operational and safety concerns beyond those experienced at other times of the year. However, growing congestion in urban areas and the drive to improve efficiency and capacity utilization on HOV networks has prompted cities throughout the nation to consider implementing HOT facilities. In the summer of 2005, the I-394 HOT facility was opened in Minneapolis, Minnesota. Other metropolitan areas that can be affected by extreme winter conditions, such as Washington DC, Denver, Seattle, and New York are presently considering or pursuing HOT facilities.

Figure 7-4. Preferential Facility in Winter Conditions

There has been no experience to date regarding safety considerations associated with HOT operations in extreme winter conditions. A limited body of knowledge exists with respect to HOV-lane performance in winter weather, but this may not be transferable to the unique operational and enforcement environment that exists on HOT facilities. Heavy snowfall or icy conditions can significantly impact the performance and safety of general-purpose lanes and HOT facilities alike. These conditions may markedly raise HOT-facility demand, increase violation rates, impact technology operations, and affect overall facility safety. Issues related to the safety and practicality of HOT-facility enforcement during extreme winter conditions may also arise. There is a need to examine these issues and monitor the safety performance of new HOT facilities in extreme winter conditions to develop a better understanding of these considerations and enhance the safety of future HOT facilities.

APPENDIX A
GLOSSARY OF TERMS AND ABBREVIATIONS

Arterial HOV Lane: An HOV facility usually located in the right (curb) lane of an urban arterial and characterized by possible interaction among HOVs and general-purpose traffic, bicycles, and pedestrians.

Articulated Bus: An extra-long, high-capacity segmented bus that has the rear portion flexible but permanently connected to the forward portion with no interior barrier to hamper movement between the two parts.

At-Grade Access: Ingress/egress between an HOV facility and the adjacent general-purpose lanes that occurs with a direct merging maneuver. Contrasts with direct (grade-separated) access.

Automated Vehicle Identification (AVI): Use of overhead or roadside detectors to read and identify vehicles equipped with a transponder or similar device. Used for electronic toll collection and traffic management.

Average Vehicle Occupancy (AVO): The number of people divided by the number of vehicles (including buses) traveling past a specific point over a given time period.

Barrier-Separated HOV Lane: An HOV lane that is physically separated from general-purpose lanes by a concrete barrier. The facility may have one or two reversible lanes or be bidirectional.

Buffer-Separated HOV Lane: An HOV lane that is separated from general-purpose lanes by a buffer such as painted striping or plastic pylons/posts.

Busway: A preferential roadway designed exclusively for use by buses.

Carpool: A passenger vehicle carrying a designated number of people (at least two, including the driver).

Concurrent Flow Lane: An HOV lane that is operated in the same direction as the adjacent general-purpose lanes.

Contiguous Access: Access treatment in which the HOV lane is separated from the general-purpose lanes by painted skip striping only. Vehicles carrying the required number of occupants are permitted to enter or leave the HOV lane anywhere along its length (also called continuous or unrestricted access).

Continuous Access: See Contiguous Access.

Contraflow HOV Lane: An HOV lane designated for peak direction travel that operates in the opposite direction of the off-peak traffic flow.

Delineation: Painted striping or other demarcation used to indicate a separation of elements such as lanes and shoulders on a roadway.

DOT (Department of Transportation): State agency responsible for administering federal and state highway funds.

Diamond Lane: An HOV lane. Term represents the uniform traffic control symbol used on HOV-lane signing and pavement markings to designate the restricted nature of the facility.

Direct Access: Grade-separated ramps that provide ingress/egress between HOV facilities and support facilities or cross streets. Ramps of this type include flyover ramps, freeway-to-freeway direct connections, drop ramps, and T-ramps.

Directional Split: The distribution of traffic flows on a two-way facility.

Drop Ramp: Direct grade-separated access ramp that "drops" to the HOV facility from An overhead cross street.

Electronic Toll Collection (ETC): Electronic system that collects vehicle tolls by means of transponders and credit-card accounts, reducing or eliminating the need for vehicles to stop at tollbooths.

Enforcement: The function of implementing and maintaining rules and regulations to preserve the integrity of HOV and HOT facilities.

Envelope: The total available cross section within which the HOV lane is constructed.

FHWA: Federal Highway Administration.

Flyover Ramp: Ramp design that accommodates direct, high-speed connections between the general-purpose freeway lanes, park-and-ride lot, or other roadway with the HOV lane. These ramps get their name because they "fly over" the roadway to provide direct ingress/egress.

General-Purpose Lane: Lane on a freeway or expressway that is open to all motor vehicles.

Grade Separation: The vertical separation of an intersecting roadways or transportation facility.

Headway: Time interval between buses on a specified route.

High-Occupancy Toll (HOT) Lane: HOV facility that allows lower-occupancy vehicles, such as solo drivers, in return for toll payments, which may vary by time of day or level of congestion.

High-Occupancy Vehicle (HOV) Lane: An exclusive traffic lane or facility limited to high-occupancy vehicles and certain other qualifying vehicles such as emergency vehicles or motorcycles.

High-Occupancy Vehicle (HOV): A passenger vehicle carrying a specified number of people (at least two, including the driver). HOVs include carpools, vanpools, and buses.

Ingress: The provision of access to an HOV lane, HOT lane, or park-and-ride facility.

Intelligent Transportation Systems (ITS): Advanced technologies and communication systems that can be used to remotely operate, monitor, and manage an HOV or HOT facility to better assure safety, operations, and improved responsiveness to incidents.

Lateral Clearance: Distance between the edge of the lane of travel and a lateral barrier or other feature. Lateral clearance is often referred to as the shoulder width.

Level of Service (LOS): A descriptive measure of the quality and quantity of transportation service provided to the user of a roadway.

Limited Access: Access treatment in which ingress and egress to and from the HOV lane is restricted to specific locations (also called restricted access).

Line Haul: Portion of a commute trip that is nonstop between two points.

Mainlane: See General-Purpose Lane.

Mixed-Flow Lane: See General-Purpose Lane.

Mode: Means of travel.

Non-Separated HOV Lane: An HOV lane containing no buffer or barrier separation with the adjacent general-purpose lanes.

Off-Peak Direction: Direction of lower demand during the peak commuting period.

Park-and-Ride Lot: Facility where individuals can park their private vehicles and access public transportation. The facility typically offers access to an HOV or HOT lane.

Peak Direction: Direction of higher demand during a peak commuting time.

Peak Period: Period in which traffic levels rise from normal levels to maximum levels.

Positive Separation: The use of physical barriers or other treatments to prevent vehicles on one portion of a facility from encroaching on another.

Queue Bypass: An HOV facility that provides a bypass around a queue of vehicles delayed at a ramp or mainline traffic meter or other bottleneck location. Also called queue jump lane.

Queue: A line of vehicles or persons.

Ramp Metering: Procedure used to reduce congestion by managing vehicle flow from local-access on-ramps. The entrance ramp is equipped with a traffic signal that allows vehicle to enter the freeway at predetermined intervals.

Restricted Access: See Limited Access.

Reversible HOV Lane: Facility on which the direction of traffic flow is changed at different times of the day to match the peak direction of travel.

Right of Way: Area of land on which a transportation facility is constructed and vehicles are entitled to pass.

Sight Distance: Length of roadway visible to the driver who is traveling along the roadway or waiting to enter, cross, or pass along the roadway. Types of sight distance include stopping sight distance, passing sight distance, and intersection sight distance.

Single-Occupant Vehicle (SOV): A vehicle carrying only the driver.

Slip Ramp: A type of at-grade access that can be used at the beginning or end of an HOV facility that provides an acceleration/deceleration taper.

Spot HOV Treatments: Techniques that may be used to give HOVs priority around a specific bottleneck or with special access to a facility.

Statistically Significant: Unlikely to have occurred due to chance alone.

Traffic Control Device: Device such as a sign, signal, or pavement marking used to regulate, warn, and inform drivers of the performance requirements essential to safe operation.

T-ramp: Direct (grade-separated) access ramp whose design forms the letter "T" between the HOV lane and the connecting park-and-ride lot or cross street.

Transponder: A credit-card sized electronic tag usually mounted on the inside front windshield of a vehicle (using Velcro) to enable electronic payment of user fees in HOT and other tolling applications.

Treatment: Technique used to achieve a desired safety or operational effect.

Unrestricted Access: See Contiguous Access.

Vanpool: Prearranged ridesharing arrangement in which groups of people travel together on a regular basis in a van.

Violation Rate: Percentage of vehicles using an HOV facility that do not meet the facility requirements.

APPENDIX B
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