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Research Supporting the Development of Guidelines for Implementing Managed Lanes

Kay Fitzpatrick
Marcus Brewer
Tomas Lindheimer
Susan Chrysler
Raul Avelar
Nick Wood
Texas A&M Transportation Institute
College Station, TX

David Ungemah
Chris Swenson
WSP | Parsons Brinckerhoff
Houston, TX

Chuck Fuhs
Chuck Fuhs LLC
New York, NY

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Kay Fitzpatrick, TTI senior research engineer, was the principal investigator. The authors of this report are:

- Kay Fitzpatrick (TTI).
- Chuck Fuhs.
- Marcus Brewer (TTI).
- David Ungemah (WSP|PB).
- Tomas Lindheimer (TTI).
- Susan Chrysler (TTI).
- Raul Avelar (TTI).
- Nick Wood (TTI).
- Chris Swenson (WSP|PB).

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ABSTRACT

Numerous domestic and international agencies either have constructed or are planning managed lanes; each facility is unique and presents issues and challenges because these facilities are often implemented in high-demand, congested, or constrained corridors. There has been no singular guidance to assist transportation agencies implementing managed lanes; various guides contain some information on managed lanes, but they do not explicitly address the wide range of issues and complexity associated with managed lanes in sufficient detail to serve as a national guide on the subject.

The objective of NCHRP Project 15-49 was to develop guidelines for the planning, design, operations, and maintenance of managed lanes. The final product—*Guidelines for Implementing Managed Lanes*—will become the primary reference on managed lanes and complement other national guidelines. It was designed to be applicable to practitioners at all levels of experience with managed lanes and to be used to support informed decision-making. The scope of this project was limited to managed lanes on freeways and expressways.

In Phase I of this project, the research team compiled existing information from published literature and existing manuals and policy documents, emphasizing sources published in the last 10 years. Researchers also discussed current practices with practitioners in group and individual settings to document guidance needs that the practitioners identified. Using information obtained in these activities, in Phase II, the research team conducted a series of focused studies to fill identified knowledge gaps on design decision-making, trade-offs of geometric design elements, access design, and factors that affect speed on managed lanes. The activities and findings of the research team on those tasks, along with potential research needs and suggested changes to existing reference documents, are documented in this report and its appendices. The final version of the guidelines is published as a stand-alone document to facilitate its dissemination and use within the profession.

EXECUTIVE SUMMARY

Managed lanes are highway facilities or a set of lanes where operational strategies are proactively implemented, such as pricing, vehicle eligibility, access control, traffic control, or a combination of these strategies. Numerous domestic and international agencies either have constructed or are planning managed lanes. Each facility is unique and presents issues and challenges because these facilities are often implemented in high-demand, congested, or constrained corridors. There has been no singular guidance to assist transportation agencies implementing managed lanes. Some information on managed lanes has been included in American Association of State and Highway Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) guides, but they do not explicitly address the wide range of issues and complexity associated with managed lanes in sufficient detail to serve as a national guide on the subject. Practitioners seek a better understanding of the unique planning, design, operations, and maintenance considerations associated with managed lanes, and how these factors interact. Managed lanes also have unique aspects related to financing, project delivery, public outreach, enforcement, and system integration that should be considered in each step of the project development process.

The objective of National Cooperative Highway Research Program (NCHRP) Project 15-49 was to develop guidelines for the planning, design, operations, and maintenance of managed lanes. The final product—*NCHRP Research Report 835: Guidelines for Implementing Managed Lanes*—will become the primary reference on managed lanes and complement other national guidelines. It was designed to be applicable to practitioners at all levels of experience with managed lanes and to be used to support informed decision-making. The scope of this project was limited to managed lanes on freeways and expressways.

The work on this project was conducted in two phases; Phase I consisted of four tasks, and Phase II contained three additional tasks. In Task 1 of the project, the research team conducted a review of literature on the planning, design, implementation, and maintenance considerations of managed lanes. A number of references serve as manuals or guidelines with national or widespread importance and are relevant to managed lane planning, design, implementation, operations, or maintenance. Researchers considered 14 such documents with information or guidance that could be referenced for multiple topics within the anticipated outline for the guidelines document that was produced as part of this project. Researchers also reviewed an additional 150 sources and summarized their information on a variety of topics related to planning considerations, design elements, implementation and deployment, and operations and maintenance; those sources are summarized in Appendix A of this report.

As part of Task 2 efforts, the research team conducted a review of current policies, guidelines, and other documents in use by agencies that operate managed lanes. Rather than attempting to review documents from every agency in the United States, the research team reviewed 36 online documents from 16 state, regional, and local agencies considered to be among the leaders and innovators in managed lanes. The agencies are located in the states of Arizona, California, Colorado, Florida, Georgia, Maryland, Minnesota, Nevada, Tennessee, Texas, Virginia, and Washington. The documents reviewed contain guidance or policy statements on a wide variety of

topics related to the planning, design, implementation, and operation of managed lanes. The information from those documents is summarized by topic in Appendix B of this report.

In a separate effort within Task 2, research team members contacted managed lane practitioners in two ways to explore priority gaps in understanding and guidance for the development of new managed lanes. The first process involved one-on-one stakeholder interviews; 18 state departments of transportation (DOTs) and regional operating agencies were contacted for one-on-one phone interviews, with 11 successfully completed. The second process consisted of a group survey conducted with the Transportation Research Board (TRB) Managed Lanes Committee (AHB35), concurrent with the 2014 TRB Annual Meeting in Washington, DC.

The purpose of the stakeholder interviews was to explore stakeholders' guidance for specific topical areas of managed lane planning, development, implementation, and operations from which operators/agencies believe they could benefit. Three primary questions were posed to interviewees:

1. For which topics did you seek guidance but found available guidance to be lacking?
2. Looking at the next 5–10 years, what emerging trends require additional consideration?
3. What lessons learned and/or best practices has your organization uncovered?

In the Managed Lanes Committee meeting, researchers provided an overview of the project and participants were asked to provide suggested areas of focus for the research effort, keeping the following two questions in mind:

- What do you wish you had known while developing your managed lane project(s)?
- What information would be helpful to you that is not readily available in other sources?

Nine research topics emerged through the course of both the stakeholder interviews and the committee discussion:

- Pricing approach and messaging to travelers.
- Access considerations.
- Interconnected facilities.
- Designing for reduced standards.
- Operational differences between one- and two-lane facilities.
- Toll system design.
- Vehicle class preferences and enforcement.
- Inter-jurisdictional issues.
- The business case for managed lanes (i.e., under what conditions do they make sense and how can they be developed).

These topics are described in more detail in Appendix C of the report.

Based on the information compiled in Tasks 1 and 2, the research team in Tasks 3 and 4 identified gaps in existing knowledge that could be explored through additional research. In some cases, these identified gaps were related to subject matter, where limited documentation of prevailing practice exists. In other cases, gaps were related to the lack of syntheses that pull

together the wealth of commonly available information so that the practitioner can more easily understand what practices are prevalent and why. The third type of gap was related to the way that material was presented in prior references. Except for the *Manual on Uniform Traffic Control Devices* (MUTCD) and specific policy and design guidance at the state and local level, there was a dearth of prescriptive guidance for topics that are often interrelated and have rather substantial safety and operational impacts on the driver experience. Prior guidance has generally been written in synthesis perspective to capture all types of practice and give a context for how each is used, without taking the next step of identifying which may be preferred or recommended and why. Researchers documented over 40 knowledge gaps and potential research ideas, which were then categorized and presented in an interim report to correspond with chapters in the guidelines document. The research team also prepared a work plan for Phase II of the project to address some of the most important knowledge gaps, as prioritized by the research team and the project panel.

In Task 5 of the project, the first task of Phase II, the research team conducted a series of studies on four topics considered to be the highest priority of the knowledge gaps identified in Phase I. Those topics included factors that affect the decision-making process, trade-offs for dimensions within managed lane envelopes, factors that affect operating speed on buffer-separated managed lanes, and factors that influence access design. Chapter 2 of this report describes a set of case studies used to develop a synthesis on the decision-making process; the two primary categories of information are project conversions (i.e., pricing implemented on high-occupancy vehicle [HOV] lanes) and new construction. The chapter provides comparative characteristics of facilities that the practitioners were responsible for designing; a summary of challenges the practitioners faced; a description of organizational and procedural practices in design; and listings of key transferable practices, identified gaps in practice, and lessons learned. Appendix D lists the actual interview questions used to prepare the synthesis, and Appendix E provides details on the regions selected for case studies.

The project included two studies on the trade-offs and effects of lane, shoulder, and buffer widths on managed lane facilities. One study gathered managed lane practitioner information on the trade-offs considered when making cross-section width decisions and reviewed this information using focus groups. The other study identified the relationship as revealed through travel data between operations and cross-section width, including the type of buffer design separating the managed lanes from the general-purpose lanes. Key measures believed to be affected by lane, shoulder, and buffer widths are operating speed and lateral position because drivers may adjust their speed or position in the managed lane depending on their proximity to a concrete barrier or adjacent general-purpose lane. Chapter 3 of this report provides the details of the research team's activities in these studies.

Chapter 4 describes a field study in which speed data from Los Angeles and Orange County, California, and Dallas, Texas, were used to investigate the variables that affect operating speed in buffer-separated managed lanes. In uncongested conditions, statistical models of the managed lane operating speed had an intercept value greater than 50 mph. Factors that were found to have the most influence on uncongested managed lane speed included geometry (in Texas), managed lane volume (in both states), presence of pylons in the buffer (in Texas), speed in the adjacent general-purpose lane (in both states), and day of the week (in both states).

The final Phase II study focused on characteristics of access to managed lanes, particularly how practitioners make decisions on what type of access to provide (i.e., continuous or restricted) and where access points should be located if access is restricted. Researchers contacted a group of practitioners with recent and/or ongoing experience in designing or implementing managed lane access to determine their current practices and desired topics for additional information. Details of the study on managed lane access, including key findings from the practitioner interviews, can be found in Chapter 5 of this report.

Based on the information compiled in the previous tasks, the research team identified gaps in existing knowledge that could be explored through additional research. In some cases, these identified gaps were related to subject matter, where there was limited documentation of prevailing practice. In other cases, gaps were related to the lack of syntheses that pull together the wealth of commonly available information so that the practitioner can more easily understand what practices are prevalent and why. Researchers updated their list of identified knowledge gaps and potential research ideas from Phase I; those needs are categorized and presented in Chapter 6 to correspond with chapters in the guidelines document.

Task 6 of the project focused on developing the final project documents including this research report and the guidelines, which has been prepared and published as a stand-alone document. A more detailed summary of the project as a whole can be found in Chapter 7 of this report.

CHAPTER 1

INTRODUCTION

RESEARCH PROBLEM STATEMENT

The sheer number and complexity of the roadway design considerations that go into the development of a managed lane (ML) system have increased. Just a few years ago, the conventional wisdom may have supported such facilities that were only access restricted with a barrier or pylon separation. Today, tolled managed lanes operate part time on shoulders in Minneapolis. Projects are being designed along elevated and depressed alignments where right of way (ROW) restricts widening, like in Atlanta and Dallas. Open (or continuous) access with no restrictions between the tolled managed lanes and the general-purpose (GP) lanes is being implemented in Seattle and Alameda County, California, along with projects that begin to form systems by starting on one freeway and ending on another, as is evidenced in Dallas–Ft. Worth. Managed lane projects are being implemented conventionally and unconventionally with an expanding array of public and private partnership arrangements. These latest examples are framing what is being designed and how the design is being evaluated and implemented.

RESEARCH OBJECTIVE

The objective of NCHRP 15-49 was to develop implementation guidelines for the planning, design, implementation, operations, and maintenance of managed lanes. The final product—*NCHRP Research Report 835: Guidelines for Implementing Managed Lanes* (*1*)—will become the primary reference on managed lanes and complement other national guidelines. It was designed to be applicable to practitioners at all levels of experience with managed lanes and to be used to support informed decision-making. The scope of this project was limited to managed lanes on freeways and expressways.

MANAGED LANE DEFINITION

Managed lanes in the context of the developed guidelines are designated (also defined as preferential) lanes and roadway facilities located on or adjacent to controlled-access urban highways that are actively operated and managed to preserve preferential service over comparable general-purpose lanes. Preferential service often implies faster travel speeds and better reliability than would be observed on adjacent general-purpose lanes that are not subject to the same level of active management. Various operational strategies are applied to preserve these benefits in response to specific goals and objectives. Most managed lanes serve long-distance mobility needs and are accordingly the leftmost lanes next to the median barrier. These lanes are typically located within a public right of way defined as a freeway corridor. They may include provisions to address needs of specific users, such as transit stations for express bus transit. They may be adjacent to other lanes and/or physically separated.

While the application of managed lanes dates back almost 50 years and covers early busway, bus lane, and HOV lane treatments, the term "managed lanes" was not commonly applied until the late 1990s. While technical and operational practitioners apply the expression "managed lanes" to a wide variety of dedicated or preferential lane treatments found on urban freeways and arterials, the public may be exposed to a wider range of terms based on how the projects are marketed and implemented locally.

RESEARCH APPROACH

The research team conducted nine tasks. Each task is listed below, followed by the objectives of that task:

- **Task 1. Conduct Literature Review.** The objective of this task was to review literature on the safety and operational effectiveness as well as the planning, design, implementation, and maintenance considerations for managed lanes.
- **Task 2. Survey Agencies.** The objectives of this task were to (a) compile policies, guidelines, and practices used by state and local transportation agencies related to managed lanes; and (b) document issues agencies are facing regarding the planning, design, implementation, operations, and maintenance of managed lanes.
- **Task 3. Develop Draft Guidelines.** The objectives of this task were to (a) develop a detailed annotated outline of guidelines, (b) participate in conference calls to discuss the outline, and (c) develop a comprehensive draft of the guidelines.
- **Task 4. Develop Phase II Work Plan and Interim Report.** The objectives of this task were to (a) develop the interim report that summarized the results of Tasks 1 through 4; (b) develop a Phase II work plan that addressed selected critical gaps identified as deserving further study; (c) submit the Phase I interim report, the Phase II work plan, and the stand-alone draft Phase I guidelines; and (d) participate in person in a panel meeting.
- **Task 5. Conduct Phase II Supplementary Studies.** The objective of this task was to conduct the approved work plan regarding supplementary studies from Task 4. The supplementary studies selected by the panel during the panel meeting following the submission of the interim report and during a phone panel meeting held later in the project were:
    - Assessment of the Roadway Design Decisions Made by Developers of Priced Managed Lanes Systems.
    - Trade-offs of Geometric Design Elements (Data).
    - Trade-offs of Geometric Design Elements (Practitioner Panel).
    - Access Design.
    - Speeds on Managed Lanes.
- **Task 6. Refine Draft Guidelines.** The objective of this task was to refine the draft guidelines using the comments provided by the panel during the panel meeting, the written comments on the Phase I interim report, and the findings from the supplementary studies.
- **Task 7. Prepare Final Documents.** The objective of this task was to prepare the final documents, which included this final report along with the stand-alone guidelines document and a PowerPoint presentation.

REPORT ORGANIZATION

This report contains the following chapters and appendices:

- **Chapter 1: Introduction**. This chapter provides an overview of the research problem and the approaches used in the research. It also presents the objectives of the project.
- **Chapter 2: Case Studies.** This chapter provides a summary of the case study interviews that captured the design treatments and practices of representative projects for different project types and approaches.
- **Chapter 3: Dimensions within Managed Lane Envelopes.** This chapter provides the findings from two Phase II studies. One study gathered managed lane practitioner information on the trade-offs considered when making cross-section width decisions and reviewed this information using focus groups. The other study identified the relationship revealed through vehicle lane position data with consideration of the type of buffer design separating the managed lanes from the general-purpose lanes.
- **Chapter 4: Speed.** This chapter documents the speed study conducting in Phase II and explores the speed relationship between managed lane vehicles and general-purpose lane vehicles.
- **Chapter 5: Access.** This chapter documents the review of existing guidelines and discussion with practitioners about current practices and information gaps related to access to managed lane facilities.
- **Chapter 6: Knowledge Gaps**. This chapter contains a list of topics identified during this project. These topics represent gaps in the knowledge and could be candidates for further study in other projects.
- **Chapter 7: Summary**. The final chapter of the report provides a summary of the research.
- **Appendix A: Literature Review**. The research team conducted an exhaustive review of the literature on topics related to managed lanes at the start of the project. This appendix provides the summary of that review, focusing on literature published within 10 years of the start of this NCHRP project and organized by topic.
- **Appendix B: Online State and Local Documents Review**. This appendix presents a brief summary of existing guidance documents published by state and local road agencies, toll road authorities, and other entities that have managed lane facilities under their purview. The review was done in 2013. As in Appendix A, the information in this chapter is organized by topic.
- **Appendix C: State of Practice**. As part of Task 2 efforts in 2013, the research team contacted representatives from a selection of state DOTs, regional and local road agencies and planning organizations, and other managed lane practitioners to inquire about current practices and potential guidance needs, based on their professional experience and the policies of their respective jurisdictions. This appendix presents the findings of those outreach efforts.
- **Appendix D: List of Interview Questions: Assessment of the Roadway Design Decisions Made by Developers of Priced Managed Lane Systems.** This appendix provides the script used during the interviews.
- **Appendix E: Case Study Regions.** This appendix details the six case study regions examined to garner insight into the local context for decision-making that led to adopted designs and local practices.

- **Appendix F: Suggested Changes to Reference Documents.** This appendix includes the research team's suggested changes to reference documents.
- **References.** This section provides the references cited in the report.

CHAPTER 2

CASE STUDIES

OVERVIEW

Capturing recent design experience and making sure it is incorporated into the latest managed lane guidance is especially critical for updating applied practice and processes being adopted. While few agency sponsors have embraced a preferred design practice, they are experimenting and demonstrating different ways of designing and implementing managed lanes with an eye toward regional consistency of process and practice. This study attempted to capture this expanding set of design treatments and practices through case studies of representative projects within regions that bracket different project types and approaches. While design basics are often documented in project descriptions, the basis for how the design came to be and what factors influenced the design and design process are often missing. There is no documented and comparative basis for understanding the latest design practice.

Objective

The objective of this study was to gain an understanding of how design decisions are being made on managed lane projects by agency sponsors. This research examined designs for existing operational projects and for those in design, under construction, or soon to open. It captured implementation approaches being applied today by providing an understanding of the design and why/how a specific design was applied. The study also delved into the influencing factors that resulted in a particular design. It provided answers on why and how certain design decisions were made including documentation of the design options that were considered and rejected. The resulting synthesis provides insight into the decision-making process being applied in the design of tolled managed lanes, which should prove to be helpful given the ever-increasing number of tolled managed lanes that are being planned and developed. The synthesis does not attempt to provide a preferred standard of practice; it attempts to capture the wide range of factors that are considered by practitioners to be locally important in planning and selecting such features as project alignment and cross-section, access, tolling systems, and related needs and requirements. It also discusses how a project was delivered if the delivery approach differed from conventional practice by the agency sponsors.

Design decision-making was defined in this study as the process from conceptual development during planning through implementation and operation when design modifications may have been made after the project opened. Findings from this synthesis were intended to inform specific guidance being developed in the NCHRP 15-49 *Guidelines for Implementing Managed Lanes* (*1*).

This documentation provides insights into the primary influences that appear to be affecting the project development process and project design, which, based on representative case studies, is not always linear and straightforward. These experiences, while not expansive

enough to form a basis for best or preferred practices, help confirm the range of practice and the factors commonly influencing design decisions.

Documentation is presented from two perspectives in Chapters 2 and 3: (a) a regional context through case studies, and (b) collective experiences for all case studies represented by the two primary types of projects being implemented. These include conversions of existing HOV lanes typically by adding electronic tolling and new construction where no prior managed lane project existed. Some project case studies represent combinations of these.

Research Methodology

The approach applied to assess decision-making was to reach out to practitioners who were most knowledgeable and in many cases most instrumental in making design decisions. The research methodology had to be responsive to limited time and budget, since it was a small part of an expansive effort to prepare updated managed lane implementation guidance. Accordingly, representative sites had to be selected to interview developers of managed lanes. The selection of sites needed to capture the following attributes:

- Inclusion of both conversion and new construction projects, with preference to regions where both approaches were being implemented.
- Single and multilane directional designs (i.e., one or more managed lanes operating next to GP lanes).
- Various project delivery approaches being applied including standard delivery, design-build, and public-private partnerships (P3) such as concessions.
- Projects involving transit facility design.
- Amount of time transpired since experiences were gained.
- Geographic distribution.
- Willingness of practitioners to share their experiences and time.

Table 1 presents a list of regions evaluated for purposes of hosting practitioner meetings. No more than five representative regions involving at least three key practitioners per region were established at the onset of this task for budgeting purposes. Noted attributes formed the basis for selection. The regions not shaded were ultimately selected based on preliminary contacts with agency sponsors to test willingness to participate. The selected regions included Atlanta, San Francisco–Oakland–San Jose Bay Area, Dallas–Ft. Worth, Los Angeles, and Seattle. This list was reviewed by the NCHRP 15-49 panel members before outreach with practitioners began. Once meetings occurred, a lack of transit facility designs at the five selected locations posed difficulties in covering the topic, so a sixth location, San Diego, was ultimately added to this list for that reason.

Table 1. Regional locations considered for practitioner data collection.

Candidate Regions and Projects*	Selection Criteria			
	Age Since Opening	Sponsoring Agencies	U.S. Geography	Type of Project
Dallas–Ft. Worth: I-635 (LBJ), I-820/SH 183 (NTE), I-35E, I-35W, US-75	<1 year	Texas DOT, North Texas Council of Governments, North Texas Turnpike Authority, Dallas Area Rapid Transit, Cintra Constructors	Central	Dual lanes, new construction, and minor conversions to single-lane HOVs
Los Angeles: I-10, I-110	2–3 years	Los Angeles Metro, Caltrans	Southwest	Dual lanes, major conversion
Atlanta: I-85, I-75/575	3 years	Georgia DOT, State Road & Tollway Authority	Southeast	Single lane, minor conversion, and new construction
Seattle: SR 167, I-405	SR 167: 5 years, I-405: 2015	Washington State DOT	Northwest	Single and dual lanes, minor conversion + new construction
Virginia: I-495	3 years	Virginia DOT, Fluor-TransUrban Constructors	Mid-Atlantic	Dual lanes, new construction
Austin: Loop 1—Mopac North	Under const.	Central Texas Regional Mobility Authority, Texas DOT	Central	Single lane, major construction
Houston: I-10W	6 years	Harris County Toll Road Authority, Texas DOT	Central	Dual lanes, major construction
San Diego: I-15	4 years	SANDAG, Caltrans	Southwest	Dual lanes, major construction
Bay Area: SR 237/I-880, I-680, I-580	2–3 years	Caltrans, Valley Transportation Authority, Alameda County Transportation Authority, Metropolitan Transportation Commission	Southwest	Single lanes, minor conversion, and new construction
Denver: I-25, US-36	3+ years	Colorado DOT, E470 Authority	Central	Dual-lane conversion and new construction, new single lane
Minneapolis	3+ years	Minnesota DOT	Central	Dual-lane conversion and new construction of single lanes
Miami	5+ years	Florida DOT, Florida Turnpike Enterprise, Miami Dade Expressway	Southeast	Dual-lane conversion and new construction

Note: Shaded locations were considered and ultimately not selected. LBJ = Lyndon B. Johnson; NTE = North Tarrant Express; SANDAG = San Diego Association of Governments; Caltrans = California Department of Transportation.
*Detailed descriptions of each project are provided in Chapter 2 for each case study.

Determining projects representing typical designs and experiences that were more likely to be transferable also contributed to the screening process. Four subset design types were sought among the projects as being the most transferable to future projects based on current plans and projects in development. These included:

- Multiple lanes, new construction. Example sites included I-75/575 and I-75S in Atlanta; LBJ, NTE, and I-35W in Dallas–Ft. Worth (DFW); and I-405 in Seattle.
- Single lane in each direction, new construction. Examples include DFW Connector, SH 183 in Irving and I-35E in Dallas; and SR 167 extension in Seattle.
- Multiple lanes in each direction involving an HOV lane conversion. Examples include I-10 and I-110 in Los Angeles.

- Single lane in each direction involving an HOV lane conversion. Examples include I-85 in Atlanta, SR 167 in Seattle, and all projects in the Bay Area.

As noted in Table 1, multiple projects were available in each region. These projects offered a breadth of design and delivery experience to address the study's objectives.

Information Sources

Information was collected from practitioners who had close knowledge of or were instrumental in the decision-making process for their respective projects and agencies. Practitioners were defined as any person employed in either a public or a private entity engaged in evaluating or authoring decisions and likely to influence the design outcome. Many practitioners served in only one stage of project development, with successive individuals being engaged in carrying the design or project delivery forward. For this reason, a goal among practitioner selection was to make sure the entire project development process was represented. Efforts were made to obtain information from the practitioner who was charged with these decisions at the time they occurred, even if the individual had moved on to other roles or employers.

This synthesis reflects the following perspectives:

- State DOTs.
- Regional transportation implementation agencies (termed congestion management agencies [CMAs] in this synthesis). Some regions also call these regional transportation or mobility authorities.
- Toll authorities.
- Metropolitan planning organizations (MPOs).
- Transit agencies.
- Private concessions.
- Consultants representing public agencies typically in a project or program management role.

Discussion Questions

An expansive list of questions forming a discussion script was developed for practitioner meetings. The basis for questions was to capture both the process that agencies went through in responding to their specific project goals and objectives and in documenting the rationale behind design selection including influencing factors. Major aspects of design from tolling systems to enforcement and incident management were included. Questions and outcomes were grouped within the script in the following categories:

- Agency and project context (background).
- Design setting:
    - Cross-section.
    - Type of separation.
    - Shoulders.
    - Access.
    - Signing, markings, and other traffic control devices.

    - Enforcement provisions.
    - Toll infrastructure.
    - Maintenance and incident management.
    - Transit facilities.
- Follow up (design or operation changes after project opening).
- Lessons learned.

The list of questions comprising the interview script is included in Appendix D.

Practitioner meetings were conducted singly and in groups through teleconferences. Some responses to questions were also provided in writing from practitioners preceding or following the meetings. The large number of questions made it difficult to obtain responses to all topics, and very few practitioners responded to all questions given the limited time they could accommodate for this effort. The focus of dialog was on how decisions were made within the project context practitioners were working under, not a comparative compilation of design details for each project. A few respondents were helpfully candid in their remarks and requested that meeting notes not be included in the synthesis.

Organization

The development of the synthesis started with developing the list of questions to use during the interviews (see Appendix D). Then, the findings were grouped into regional case studies (see Appendix E). The findings from the regional case studies were grouped by decision-making approach (see Decision-Making by Implementation Strategy section). The regional case studies in Appendix E comprehensively address the agency relationship context that is unique to each region and explore how a multitude of projects with varying characteristics was implemented. The case studies are presented in alphabetic order by region and include Atlanta, Bay Area (San Francisco–Oakland–San Jose), Dallas–Ft. Worth, Los Angeles, San Diego, and Seattle. While many topics are common for each case study, the list of topic categories is not entirely consistent or comprehensive due to the emphasis given in feedback by practitioners to certain issues and experiences they felt were most noteworthy. For example, if project delivery was conventional, it is not mentioned. If project delivery involved innovations or agency partnering experiences, the topic is elaborated in more detail. The resulting areas of emphasis may not be representative for a larger set of case study experiences, nor should they be considered representative if a larger number of practitioners were interviewed for each region. Data presented vary depending on the time afforded for dialog, the number and backgrounds of subject matter experts interviewed, and topics considered relevant to the respective agency staff. No attempt has been made in Appendix B to interpret or validate the accuracy of the information against other project data sources. Dialog in the presented case studies reflects commentary of those interviewed, and collectively, the interviews form the basis for information compiled in subsequent chapters. The outcomes of these findings were intended to help confirm where the industry and its practitioners seem to be heading in developing projects and inform and validate guidance being prepared in *NCHRP Research Report 835: Guidelines for Implementing Managed Lanes* (*1*).

The project-specific perspective in the Decision-Making by Implementation Strategy section provides insights into common challenges, transferable innovations, gaps in practice, and lessons associated with each project approach. This difference is significant since the goals associated with each are focused on either improving facility efficiency or generating meaningful revenue to offset cost. The degree of impact and design context is quite different. Conversions usually attempt to minimize cost and design and operation impacts to the existing HOV facility, often representing a modest change to an existing project. New construction more typically attempts to address vehicle capacity needs with the latest design standards appropriate for any new roadway. Decision-making is influenced by these differing requirements regardless of the regional context.

DECISION-MAKING BY IMPLEMENTATION STRATEGY

This section examines the comparative approaches to decision-making within the representative locations presented by case studies in this chapter.

Conversions

Project conversions in this context refer to tolling-based improvements implemented on HOV lanes. Some projects only added tolling, while other projects also modified the roadway to incorporate either access changes (I-85 in Atlanta) or added lanes onto existing pavement (I-10 in Los Angeles). Design and development decisions for conversions among some of the case study locations were influenced by the U.S. Department of Transportation (USDOT) Urban Partnership Agreement/Congestion Reduction Demonstration (UPA/CRD) grant program that provided matching funding if projects adhered to a rigorous schedule, and they were granted demonstration status. Had this federal program not been in effect, it is unlikely that all of the candidate conversions would have occurred, and design decisions might have been different. In particular, some observations from the limited case study settings revealed the following positive consequences from this program:

- **Limiting scope.** Adhering to a fixed schedule and budget forced sponsoring agencies to stay focused on what could be accomplished in the project design. This meant that scope creep was avoided, but not all agency practitioners could get everything they felt was needed. In some cases, this condition kept legacy designs from being updated and prevented some operational needs from being addressed. Outcomes could have been different had the projects taken a more conventional development path and timeline.
- **Agency partnering.** Numerous practitioners interviewed indicated that the UPA/CRD program forced them to work with other local agencies for the first time or brought them closer in a spirit of cooperation that was both unique and challenging. They gained respect for the unique skills and resources each could bring. Building these relationships has fostered other opportunities for partnering.
- **Internal coordination.** In at least one case, not all agency participants with decision-making or reviewing roles understood or appreciated the significance of adhering to the grant tenets for rapid delivery. The project had to be treated in an extraordinary way with upper-management support to achieve desired results. It is unlikely that similar projects to follow would be granted this same latitude.

- **Design trade-offs.** Hard choices were made that resulted in application of practical design some practitioners might consider inappropriate for long project life cycles. The short-term nature of these demonstrations allowed for such approvals, and this process helped generate a better understanding of how resulting designs and operations perform.
- **Dynamic tolling.** Practitioners interviewed in Atlanta, Los Angeles, and Seattle had never applied tolling on an interstate before, so they and their partner agencies gained new skills and knowledge in applying dynamic tolling, and they have gone on to further advance use of this tool.
- **Multimodal accommodation.** Some projects included funding for non-highway improvements, allowing all participants to better appreciate and understand how express lanes and transit needs can be met.
- **Project delivery.** In order to maintain schedules and share or shed risk, various project delivery approaches were applied that were new to some agency partners, and selecting this approach for a tolling systems provider was particularly beneficial.

Comparative Characteristics

Table 2 provides a summary of characteristics associated with the representative projects from the case studies. They reflect both dual and single directional lane treatments.

Table 2. Comparative project characteristics for conversions.

Project Location	Number of Lanes	Status	Separation	Type of Access	Project Delivery	Changes Made
I-85 Atlanta	1/direction	operational	2-ft buffer	restricted	DBF*	Added tolling, raised 2+ to 3+ and registration, restricted access
I-680 Bay Area SB	1/direction	operational	2-ft buffer	restricted	DBB*	Added tolling, restricted access, and now opening access back
I-680 Bay Area NB	1/direction	being developed	2-ft buffer	restricted	DBB*	Adding tolling
I-880 Bay Area	1/direction	being developed	2-ft buffer	half open, half restricted	DBB*	Adding tolling, restricting some access
SR 237/ I-880 Bay Area	1/direction	operational	2-ft buffer	restricted	DBB*	Adding tolling, restricted access
I-10 Los Angeles	2/direction	operational	2-ft buffer	restricted	DBOM	Adding tolling and registration
I-110 Los Angeles	2/direction	operational	4-ft buffer	restricted	DBOM	Added tolling and HOV registration
SR 167 Seattle	1/direction	operational	2-ft buffer	open	DBB*	Added tolling, initially restricted access, now open access

Note: DBB = design-bid-build (conventional delivery); DBF = design-build-finance; DBOM = design-build-operate-maintain.
*Tolling system was provided either design-build (DB) or through an on-call toll vendor under separate contract.

Challenges Faced

Three groups of challenges were faced by practitioners. These included procedural (P), organizational (O), and design-related (D) issues. They are presented below in order of times mentioned or referred to in collective dialogs:

- Limited right of way (D).
- Staying within edge of existing pavement (D).
- Tight schedule, driven primarily by the UPA/CRD grant requirements (P).
- Staying within budget (P).
- Inherited legacy design and operation from HOV lanes (D).
- Design exception identification, evaluation, and approval (D).
- Lack of prior tolling or alternate delivery experience (O).
- Provision of enforcement areas/treatments (D).
- Addressing updated practices and procedures (P).
- Integrating other modes, particularly transit, into the project (O).
- Signing: pricing, branding, access, regulatory (D).
- Determining the type of lane separation or access to provide or change (D).
- Sight distance and drainage treatments (D).
- Agency partnering (O).
- Political intervention/need for outreach and education (O).
- Policy and legislative directives (P).
- Environmental/project development hurdles/environmental justice issues (P).
- Consistency of practice (P).

These challenges were influenced by the types of practitioners who were contacted, and most were engineers, project managers, or agents serving to support these disciplines. Their perspectives as developers reflect the uncertainties often associated with projects that are similar yet different from mainstream highway work engaged by a state DOT. Some challenges illustrate the difficulties practitioners encountered in trying to convert an HOV project that was in many places already burdened with many prior constraints and design exceptions. Opening these projects up to scrutiny by a new generation of evaluators and reviewers and often dealing with updated standards and procedures had differing, and sometimes frustrating, results. Some practitioners were able to assume these prior conditions and move forward; others wanted to revisit past decisions and attempt to improve upon them as part of the conversion process or to improve upon the entire roadway's deficiencies. USDOT demonstrations forced hard decisions on respective practitioners, which did not provide much latitude for this opportunity. This experience is perhaps why the comments are weighed more toward procedural and organizational challenges than might otherwise have been expected. These same challenges might be expected for design-build or P3 approaches.

Perhaps a clearer illustration of the difficulties in adhering to standards and protocols can be found in Table 3, which shows the number of categories in which designers were required to make a decision on whether to meet standards or accept a practical design that deviated from their own or national guidance. Most projects in many categories faced this challenge. A few agencies, notably Caltrans and Washington State DOT (WSDOT), had informal or adopted protocols to help them make informed trade-offs. This guidance was not consistent in each

case with national guidance but shows that tools are being applied to help the practitioner reach a decision with a means of defending what are otherwise hard choices that carry a safety implication. While trade-offs generally reflect practitioners' willingness to give up left shoulder or buffer widths before reducing lane widths, practitioners seem to prefer flexibility in making judgments at the project level to having prescribed trade-offs. A widespread sentiment supports not reducing each component below certain set minimums, which are typically described as 2 ft for left shoulders and buffers and 11 ft for lane widths. Washington considers using a 2-ft buffer as more of a standard than a 4-ft buffer, and other areas including Atlanta and northern California have implemented projects with a limited-width buffer. Preserving an outside shoulder width sufficient to facilitate disabled vehicles was particularly important to practitioners.

Table 3. Impact of projects on prevailing design standards.

Compliance with Prevailing Standards for Width*					
Project/Location	**Left Shoulder**	**Express Lane Width**	**Buffer**	**Adjacent GP Lane Widths**	**Outside Shoulder**
I-85 Atlanta	No	No	No	No	Yes
I-680 Bay Area Southbound	No	Yes	N/A	Yes	Yes
I-680 Bay Area Northbound	No	Yes	N/A	Yes	Yes
I-880 Bay Area	No	Mostly	N/A	Mostly	Yes
SR 237/I-880 Bay Area	No	Yes on connector	Yes	Yes	Yes
I-10 Los Angeles	No	No	No	No	Mostly
I-110 Los Angeles	Yes, except at access points	Yes	Yes	Yes	Yes
SR 167 Seattle	No	Mostly	Yes	Mostly	Varies

* All projects required design exceptions for either initial HOV retrofit or conversion.

Organizational and Procedural Practices in Design

The Role of Partnering

Agency partnering in many of the subject locations researched was not new and not just associated with managed lanes. Public-public partnering on managed lanes involving some of these same corridors, like I-10 in Los Angeles, dates back to the 1970s. The benefits to partnering in locations where such has occurred cannot be understated, and partnering has happened in a majority of instances, increasingly so for UPA/CRD grantees. The greatest leverage among agency partners seems to have occurred where each agency's resources and capabilities were brought to bear in a time-constrained manner to achieve quick results. State DOTs have only recently been engaged in tolling, whereas some partners had such capabilities or were able to acquire them more easily and quickly. The roles of enforcement and transit of agency partners are particularly noteworthy among the case study examples.

Where they were involved early, a better outcome resulted. Where they were not engaged at the right time, a lesson learned was mentioned in the practitioner responses. Practitioners in leadership positions who have crossed over to other agencies have gained a unique perspective that has helped foster relations.

Placing boundaries around what roles each agency partner will play in development helps streamline responsibilities. The early and collective adoption of a concept of operations (ConOps) document outlining the intended operation and design has played a major role in defining the skill sets required to implement the project among agency partners, which in turn helps establish who does what. While partnering has had its ups and downs in some locales working through such roles, for the most part, the projects and their institutional support are stronger for these implementing agency relationships and the innovative project delivery experience and design concepts that emerged from them.

Procedural and Evaluation Practice

When comparing planning and development procedures to the project objectives, discussions indicated that conversions to add tolling addressed two rationales: over- or underutilization of the HOV lane. However, improving lane management through pricing can be a more polarizing tactic than, say, increasing enforcement or changing occupancies during a degraded period. Greater focus is a likely outcome since the attributes of adding tolling to a roadway trigger more intense scrutiny from more stakeholders; multiple disciplines are involved at more detailed levels. Environmental regulations in particular may require a much greater need for study and potential mitigation that HOV lane operational changes have not historically faced. Federal policy and guidance for congestion pricing demonstrations were initially highly regulated on interstates and were only recently opened up to mainstreaming for conversions. This legacy continues to create confusion and uncertainty within respective agencies, particularly when agency partnering is involved.

An examination of the objectives frequently mentioned in Table 4 shows that there is commonality between both conversion rationales. While some projects, like SR 167, had capacity to offer, just as many projects being converted were oversaturated prior to actions being taken. These conditions suggest that any conversion outcome in these cases would create some legacy winners and losers since all prior users could not be accommodated within the same point in time. Impacts of some sort would occur that would need to be mitigated. These cases indicate that in order to minimize overall impacts to legacy users (which was a stated objective in many cases), such actions would necessarily reflect very short-term Day 1 impacts and not necessarily warrant longer-term (10- or 20-year) evaluations. Such impacts are modest in nature, particularly from the capacity associated with a single lane when trying to evaluate macro-level impacts associated with an entire freeway or corridor involving other parallel routes. For such subtle changes, no simulation tool has been deemed practicable, perhaps for short-term consideration and certainly not for longer-term horizons. Practitioners have become disillusioned when trying to ascertain the value gained from such tools unless the objective is broadened to address a much wider array of strategies or improvements that can be measured. Too often, results have not satisfied reviewers and led to process creep. Various responses to this dilemma were documented. Some projects were opened with limited

operational studies performed to assess impacts, while others consumed many months or years trying to reach closure on impacts to mitigate.

For oversaturated conditions, conversions categorized as operational actions may not rise to the level of representing a new construction project with the associated scrutiny. Being the first projects in each region may have justified such scrutiny; however, after initial monitoring, subsequent conversions in a given area may give credence to a less intense process or method for project evaluation and adoption. Perhaps no single issue represented more frustration among practitioners than the need to have a clearly defined method for evaluating such operational changes in this context. There was a general sense that too much effort and too many resources were expended to address conversions as standard highway projects, which adversely impacted time, budget, and scope to move forward. A more scalable approach to planning and evaluating improvements to an existing project was an expressed need. Only one agency, Caltrans, has a policy directive (*2*) that attempts to accomplish this, yet it combines operational and capacity situations and is not prescriptive or fully supportive of this need based on feedback received.

Table 4. Objectives associated with conversions.

Most Frequently Mentioned Major Objectives	**I-85 Atlanta**	**I-680 Bay Area SB**	**I-680 Bay Area NB**	**I-880 Bay Area**	**SR 237/I-880 Bay Area**	**I-10 Los Angeles**	**I-110 Los Angeles**	**SR 167 Seattle**
Improve person throughput	Yes	Yes				Yes	Yes	Yes
Manage vehicle throughput	Yes			Yes	Yes	Yes	Yes	Yes
Ensure reliability	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Demonstrate tolling	Yes	Yes				Yes	Yes	Yes
Improve enforcement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Promote transit	Yes					Yes	Yes	
Minimize HOV user impacts		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regain benefits	Yes			Yes	Yes	Yes	Yes	
Generate revenue	Yes	Yes		Yes	Yes			Yes

Design Practices

This research revealed the importance of having all agency stakeholders at the table early on for both determining the conversion concept and executing it. Stakeholders are tied to the goals and objectives established, but at a minimum, there is a need to involve those operating, tolling, and enforcing the express lane. The blueprint for effective design is generated from the concept of operations, which has taken a more prominent role than it would for a typical highway project. This prominence is created from the newness of the concept to sponsoring agencies, the emphasis on operation that must be accounted for in the adopted design, and the frequent need for close coordination among different sponsoring agencies.

The conversion process allowed some agencies to reassess their accepted standards of practice in how they had been implementing HOV lanes. In most cases, a generational shift had

occurred between the time the prior HOV design was implemented and the conversion was undertaken, notwithstanding extensive population and travel growth. This institutional knowledge gap was a potential positive outcome because the conversion process shook up the status quo. This is particularly true for projects like I-10 in Los Angeles, which had noncompliant HOV signs. The life cycles for most projects had been exhausted, and high-occupancy toll (HOT) lane conversion refreshed some of these projects to better if not current standards based on recent practice. Some practitioners were proactive in their assessment that they were still learning from their first experiences, and close monitoring would help them better understand what works and what needed further refinement or modification. Some examples follow:

- The SR 167 project started with restricted access because toll gantries were placed far apart, and the cost to implement could be low based on this design. However, customers frequently violated the buffer-restricted segments. The weave zones were extended in response, but violations still occurred. The state DOT obtained a grant to reopen access to the prior legacy condition and will monitor results. Additional toll gantries may now be required if customers weave in and out to avoid tolls.
- I-85 began as a heavily instrumented project with capabilities to manage toll collection and buffer-crossing violations. Some access changes were made and are being planned to address high-volume locations.
- I-10 and I-110 operational monitoring has identified a need for more toll gantries to better track and manage the lanes.
- Many projects experienced tolling and operational issues that required design changes after opening. Atlanta, Los Angles, and Seattle have all had to adjust their perspectives on how tolling can be used to better manage demand. Signing and pavement marking changes have been the most common modifications required to adjust to changed operating conditions.

Transferable Practices

A large number of conversions are planned looking forward. Practices applied by project sponsors that should be considered on other projects in similar design contexts include the following:

- **Cross-section.** Recent common practice in very restricted design settings includes consideration of reduced inside shoulders to no less than 2 to 4 ft, travel lane widths to 11 ft, and buffers to 2 ft. Vertical barrier face is applied to bridge and sign columns. Point-specific reductions to no less than the above reductions are common. Around toll gantries, median barrier widths up to 4 ft are typical.
- **Agency partnering and innovative delivery.** Planning, designing, building, operating, and maintaining express lanes represent valuable partnering and project delivery lessons. Conversions have taken advantage of these practices, particularly for installation and operation of tolling systems. State DOTs are getting more flexibility to use innovative delivery tools, while some partner agencies already had this flexibility. Tolling and communication systems, in particular, were often subjects of vendor contracts that provide operation/maintenance functions through a technology's life cycle. Most every project is taking advantage of some form of vendor for these functions.

- **Access.** Design treatment for project access has two standards of practice for concurrent designs: restricting access to designated locations and opening the project to open access. Within a relatively recent time frame, some projects have tested both approaches. Some projects with access restrictions have added access (I-85 in Atlanta); some have lengthened access zones (SR 167 in Seattle), and some have either removed or plan to remove access restrictions in favor of open access (SR 167 and I-680). Policies and practices favoring one approach or the other have been adopted in various regions, and designs are available for both among at least three projects in multiple states.
- **Enforcement treatments.** Facility design practice is increasingly being shared among projects. For example, beacons located on the rear side of gantries for single-lane enforcement monitoring and mobile applications both at monitoring sites and as officers travel in the lane allow officers to more easily determine who has an active account and whether they have paid. The application of beacons at fixed monitoring sites was first applied over 15 years ago and is now more commonly adopted among projects. Enforcement monitoring areas near toll gantries are being placed in the median to offer police a safe refuge to view traffic and pursue violators.
- **Tolling installations.** Single-pole gantries for tolling systems or side mounting on median barriers are becoming accepted practice. Prior installations required a 40-ft separation between two gantries in order for cameras to capture front and rear license plates and provide adequate illumination. Latest technology and lighter-weight equipment reduce this need.
- **Maintenance.** While many aspects of maintenance remain the same as for any freeway setting, toll and signing technology is advancing such that provision for maintenance in the field can be reduced, with more troubleshooting occurring off-site. However, maintenance needs in the field are critical and need to be considered to maintain operational reliability.
- **Drainage.** Restricted settings next to the median barrier requires retrofitting drainage—catch basins, slotted drains, and other strategies—to prevent ponding in the travel way. These changes can result in more extensive maintenance needs if slotted drains are adopted.
- **Performance monitoring.** Various agencies are tracking their projects closely, and some will be documenting findings that will continue to inform best practices and adoption of local policies. Efforts should be made to disseminate findings and allow for updates in guidance.

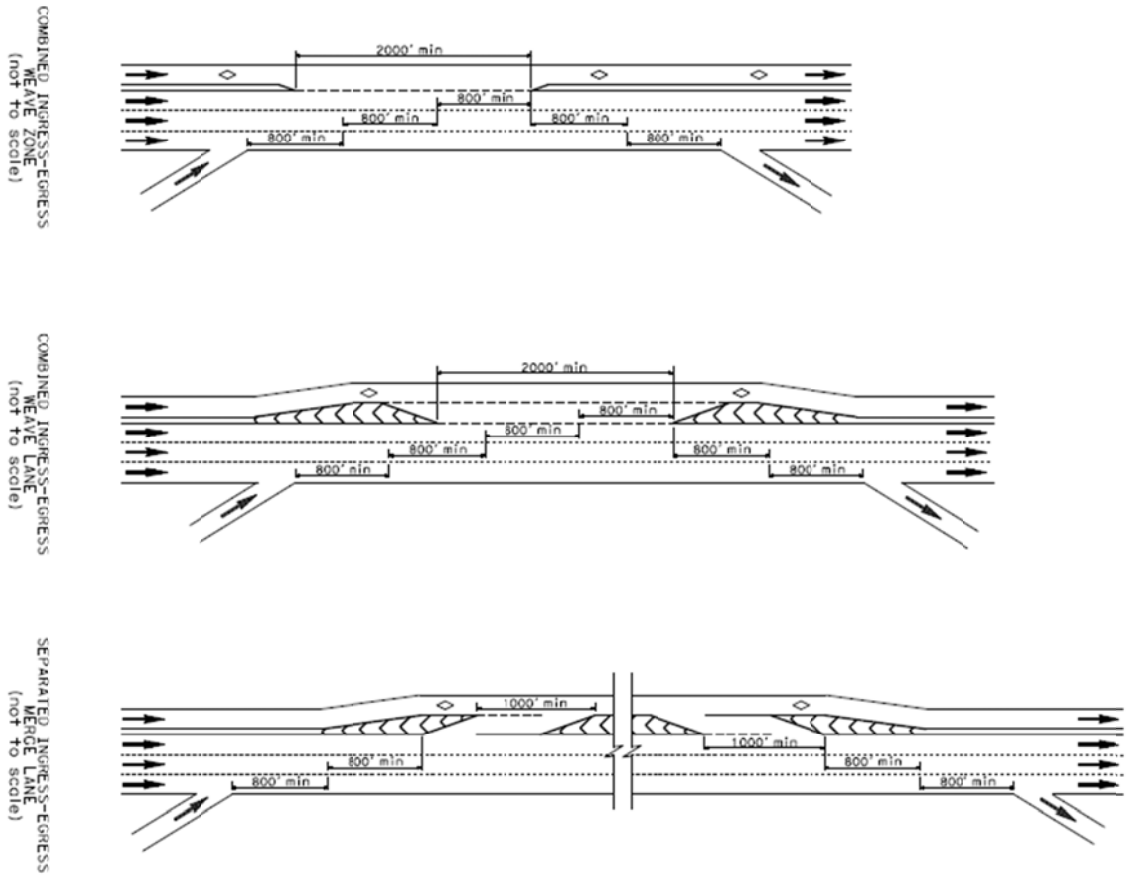
Gaps in Practice

The subject projects reflect topics that have not found a satisfactory design resolution in some cases. These include the following:

- **Evaluation procedures.** A simpler means of evaluating lane conversions based on current situations and experiences is needed to address a prevailing philosophy among some practitioners that impacts can be measured and mitigated.
- **Occupancy enforcement.** An automated means of performing occupancy enforcement is still a problem when allowing HOVs to operate at a free or discounted rate. Embracing such technology has been a long-sought solution. Latest technology demonstrations suggest that 95 percent accuracy is possible, which means such a tool

could augment, but not replace, on-site police presence to determine if there is a field enforcement need. Project design still needs to account for on-site visual monitoring. Provision of design treatments is limited on space-constrained projects, which outnumber those with adequate shoulders. Agencies are trying different designs in the vicinities of toll gantries to provide at least enforcement monitoring capability. No design has proved to be efficient or particularly effective for apprehension, and new projects are opting to avoid this issue by tolling all but transit vehicles.

- **Access experience.** Several access concepts are being demonstrated (see examples from Caltrans (*2*) in Figure 1). Each involves a range of rationales and trade-offs that should be documented.



Source: California Department of Transportation, Copyright 2014, all rights reserved (*2*)

Figure 1. Restricted-access options developed by Caltrans.

- **Regional system management.** These early projects have provided great examples of demonstrating how different modal needs can be integrated into the project design, including transit. However, a similar integration issue related to common system monitoring for a region's express lanes or from each region's traffic control center remains elusive. Most projects currently have their own monitoring function housed within the operating sponsor's office, separate from the centralized facilities that monitor all freeways. This practice has helped ensure extraordinarily close monitoring for these demonstrations, helping make them successes from the time they

were launched. As more projects are added, inefficiencies occur when separately managing the different lanes of the same roadway.

Lessons Learned

Following is a compilation of lessons learned from discussions held with design practitioners involved in conversions of HOV lanes to HOT or express lanes.

- **Define the need and scope.** Define the project goals and the problems the project is going to solve, and get buy-in from the disciplines and reviewers involved. Confirm with other decision makers the scope and context of the project, along with the level and type of evaluation needed and warranted. Determine which agency disciplines/departments are responsible for leading and evaluating.
- **Expect changes.** Design changes should be expected for the first years of operation. These typically involve signing, access, and other traffic control revisions. Georgia DOT is adding pylons for a short stretch of I-85, Washington State DOT is testing an open-access approach to SR 167, and Bay Area agencies are changing their original I-680 pilot project by opening access and improving toll efficacy with license plate reading cameras.
- **Minimize impacts to HOVs.** For conversions and first toll projects in a region, the mantra should be "no losers," at least initially. User preferences and legacy design and operation weigh heavily on the customers and their ability to adapt to changes.
- **Create transparency.** Closely evaluate costs and benefits going into a project to establish perceptions based in reality. This can help better focus the scope on a design outcome that is adjusted to these parameters.
- **Examine modal opportunities.** Look at opportunities to link other transportation alternatives and improvements than just implementing tolling. Try to address all affected modes.
- **Create agency partnering.** Having strong partnering agencies and maintaining close coordination has been critical to effective design, implementation, and operation. Champions within the implementing agency(s) need responsibility and authority to work with their peers to make decisions that often hinge on best judgment when addressing non-standard design trade-offs. Establish agreements (joint use/cooperative agreements, maintenance agreements, tolling agreements, etc.) as early as possible.
- **Focus on environmental requirements.** Confirm how to apply environmental requirements today to projects that represent subtle operational changes, such as conversions that may have limited documented impact on overall corridor management efficiency. Environmental justice sensitivity will always be important when tolling is a management strategy.
- **Create concept of operation.** The earlier the business decisions get made, the better. Operational policies, such as a carpool policy, should be determined as early as possible to limit later changes. The design should not be in flux late in the process. Business rules reflected in the ConOps need to be agreed to and locked down; otherwise, the project will suffer delay and cost overruns. Following best practices in systems engineering, the ConOps and system requirements should be fully developed and finalized before finalizing the civil and system designs.

- **Ensure early engagement.** Enforcement, emergency, and maintenance personnel should be involved early in the ConOps and design process. Some projects did this well and were pleased with results.
- **Consider gantries.** The potential for more lightweight structures for mounting of tolling antennas might be considered. This practice would be dependent on many factors, among them the requirements for accuracy for the tolling system integrator.
- **Ensure design coordination.** From a contracting standpoint, three types of procurements best capture the needs of a system—the general civil, the toll system integrator, and the back-office integrator. How these support one another can be complicated if not properly specified. Toll integrators should be on board prior to finalizing a civil design-build procurement to allow them to review the requirements, reducing changes later in the civil design and construction processes. Be flexible and adaptable to changes in design and technology that ripple through the project development process. Changes in access preference or improved mobile applications are examples of this.
- **Ensure construction coordination.** The hand-off point between the civil contractor and the toll system integrator needs to be carefully considered. The standard is likely to be "which entity does which task in the best manner?" Site turnover rules from the contractor and integrator should be tightly specified. A sign unveiling plan as part of design should be considered as the contractor completes phases of work before the entire project is finished.
- **Perform field testing.** The need for end-to-end on-site testing is critical, often requiring more testing time than planned. Once installed, the field-testing environment is made difficult by working around traffic, most often on weekends and at night.
- **Perform surveillance.** Extra cameras to monitor express lanes operation while incidents occur is a plus.
- **Enforce tolling.** Tolling infrastructure needs a comprehensive strategy to address potential violators and evaders. More tolling gantries than anticipated are often needed.
- **Focus on project delivery.** Consider alternate delivery to share or shed risk when such concerns as schedule are paramount. Consider incentive programs within contracts if allowable, which helps ensure on-time delivery.
- **Focus on signing.** Sign design should be finalized as early in the project development process as possible. Designs and layout should be reviewed by a broad group of internal stakeholders including management to ensure that they buy into the proposed design.
- **Review specifications.** Civil engineering procurement specifications for toll-related items are different from those for a standard highway project. Specifications should be reviewed by affected groups who may work or operate a particular piece of the system.
- **Monitor performance.** Close performance monitoring of a first project is critical to improving on the second project, and in eventually adopting local and state standards of practice.

New Construction

Projects that involve new construction are those that added roadway capacity in some form and required widening or reconstruction. These projects create a freeway within a freeway, at least from a standpoint of design speed and application of design standards. Some prior HOV lanes are being incorporated as part of these projects. Examples include I-405 in Seattle and I-35E in Dallas.

Comparative Characteristics

Table 5 provides a summary of characteristics associated with the representative new construction projects from the case studies. They reflect both single- and multiple-lane concurrent and reversible designs.

Table 5. Comparative project characteristics for new construction.

Project/Location	Number of Lanes	Status	Separation	Type of Access	Project Delivery
I-75/575 Atlanta	1–2 reversible	construction	barrier	slip, drop, flyover	DBF
I-75 South Atlanta	2 reversible	construction	barrier	slip, flyover	DBF
I-635 LBJ Dallas	2–3/direction	Phase 1 open	barrier	slip, flyover	P3 concession
SH 183/I-820 Ft. Worth	2/direction	open	barrier	slip, flyover	P3 concession
SH 114/121 DFW Connector Dallas–Ft. Worth	1/direction	open	barrier	slip, flyover	DB
I-35E Dallas-Denton	1/direction	construction	barrier	slip	DB
I-35W Ft. Worth	2/direction	construction	barrier	slip, flyover	P3 concession
SH 183 Extension Dallas	1/direction	construction	barrier	slip	DB
I-405 Seattle	1–2/direction	construction	barrier	slip, drop, flyover	DB
SR 167 SB Extension Seattle	1 SB only	design	barrier	open	DB
I-15 San Diego	2/2 or 3/1 reversible	open	barrier	slip, drop, flyover	DBB

Note: DBB = design, bid, build (conventional delivery); DB = design-build; DBF = design, build, finance; P3 concession = often includes private design-build-operate-maintain-finance roles in a long-term agreement.

At least half involve full reconstruction of the prior roadway including pavement and structure replacement; the balance of the projects involves widening. While a large percentage of the projects included in Table 5 are being implemented with barrier separation, this attribute is a bit misleading since two projects require barriers because they are reversible and the rest provide barriers because this form of separation is a locally preferred policy by the sponsoring agencies. Options for a preferred design are substantially broader when right of way and cost impediments are factored in. Nationally, new construction reflects a sizeable number of buffer-separated managed lanes restricted through paint stripes and/or pylons.

Challenges Faced

The types of challenges mentioned for major managed lane projects differed substantially from those given for conversions and took on characteristics of any large urban infrastructure endeavor. However, in many locations, the project developer roles were shared between a greater array of public and private entities than observed in the past. The below list of challenges is generally arrayed based on the number of times each was mentioned in an interview. Topics included procedural (P), organizational (O), and design-related (D) issues:

- Funding/financing (P).
- Right-of-way constraints (D).
- Environmental impacts/environmental justice issues (P).
- Project development hurdles/design consensus among partnering agencies (P).
- Political intervention/need for outreach and education (O).
- Lack of prior tolling or alternate delivery experience (O).
- Need for policy and legislative tools (P).
- Maintenance of traffic during construction (D).
- Determining the type of lane separation or access (D).
- Consistency of practice (P).
- Risk and sharing of risk with partnering agencies (O).
- Agency partnering (O).
- Staying within budget (P).
- Avoiding major interchange reconstruction (D).
- Signing: pricing, branding, access, regulatory (D).
- Staging/phasing (D).
- Integrating other modes, particularly transit, into the project (O).

Organizational and Procedural Practices in Design

Developers of managed lanes in the various locations interviewed went through many gyrations before reaching closure on a concept design. The challenges faced were more expansive than any they had previously expected or encountered when highway projects were more accepted, when public and political engagement was more prescriptive, and when funding was more assured and less a part of the design decision-making process. This decision-making path was not always linear. Few cases where a single agency was in control of this process were identified. Many interviewees indicated that agency partnering strengthened decision-making and in many cases led to a better means of resource sharing and allocation. While these influencing factors might be common today with any major urban transportation project, the variables in play for a managed lane that must generate revenue to offset its cost place more complex hurdles and opportunities to make the project a reality. Current design and process guidance fails to appreciate the iterative nature of these realities. In retrospect, the lack of financing and legislated tools to expand agency funding leverage may have played a role since this evolution happened as a backdrop to these case study experiences. In a world where financial feasibility has become so critical, flexibility in starting over at multiple points in the process may not be simply a potential risk but a likelihood if this feasibility is not accounted for up front and during the environmental and design stages. Seeking and applying the right evaluation tools, legislative authorization, and

policy guidance can take time. Some projects have had a very long lead time to be implemented. Innovative delivery tools have helped regain some of this lost time. As one practitioner explained, "We were late in getting any projects opened, but we will have more opened within the next five years than anybody else."

The Role of Partnering

Agency culture and practitioner roles have often been turned upside down in this process. Some state DOTs had to be re-engineered to take on the challenges of delivering projects that carry as much emphasis on financial feasibility and design feasibility. Simultaneous to the emergence of pent-up, unfunded demand for urban highway capacity, a variety of parallel local and state agencies have risen to meet transportation needs, often with their own legislative authorization and funding mechanisms to address local or regional transportation infrastructure. These include toll authorities, CMAs, and MPOs, who have become implementing and operating agencies in support of the state DOT. Having more diverse agency partnering resources to bring to bear on transportation need has been more blessing than curse. The varied perspectives and funding and contracting capabilities have helped agencies collectively find creative solutions to complicated projects, all while sharing risks and rewards. If the project lead is not a state DOT or other federal funding recipient, and if the project is not subject to some sensitive environmental or regulatory controls, the project team may not be subject to the state DOT rules and regulations. Forging these relationships can be initially bumpy, and they have resulted in a need to organizationally recognize and formalize agreements of who does what.

In short, local or regional agencies in states with more than one congested urban area are playing a bigger supportive role to state DOTs in managed lane planning and development. In some respects, regional agencies carry a greater responsibility in representing local constituents' interests and in ensuring that in some regions, revenues received are reinvested and accounted for locally. Local agencies may be more capable of addressing and mitigating environmental justice issues without the burden of statewide policies. Increased legislative and local policy oversight may be more likely for any urban toll project being implemented on an existing toll-free highway. Federal provisions relaxing approvals for tolling have not diluted this local concern and potential push-back.

The introduction of private partners and industry perspectives into this mix has also had positive outcomes. The Dallas–Ft. Worth examples, in particular, show how a dialog that occurred through both design-build and P3 procurements helped make projects more financeable, feasible, and buildable. However, the sponsoring agencies had to be willing to accept major changes to their initial design and take risks that altered designs would result in better outcomes. These changes were in some instances radical. Entire concepts were subject to change, including potentially reopening of the environmental process. Such examples include a total change in concepts (from reversible to dual concurrent lanes in Dallas; concurrent lanes to reversible lanes in Atlanta); alignment (from tunnel to depressed-stacked roadway); project limits (combining two routes and casting off part of another); phasing (opening some segments before the total system was operational); and access (adding or taking away access to a specific community or group of stakeholders). Design exceptions to adopted design preferences or standards, even for major projects involving new right of way,

are still required. Agencies sponsoring procurement through DB and P3s had to have flexibility to accept such alternative design concepts and react to them in a manner respectful to the process and outcomes. Accordingly, the design process and decisions made from this process have resulted in a much wider palate of options than previously applied for managed lanes. There is little wonder that practitioners are seeing a wider choice of options to consider—all considered safe and effective strategies. Innovation has not been an overused buzzword; it has become an accepted means of developing and delivering projects.

Design Practices

As a backdrop to the partnering aspects that influence process and organizational roles, design practice is influenced by project objectives. These objectives are primarily focused on adding and managing new capacity in such a way that the project can be made financeable and buildable. The fundamental difference is in the scale of investment. While conversions attempt to better micro-manage traffic problems that are already obvious, new construction looks to manage added capacity and maximize both operational benefits to a larger proportion of corridor traffic/users while also seeking to repay at least a part of the cost. Design practice must be responsive to both needs. These objectives are summarized in Table 6.

Design practice reflects wide-ranging site conditions that include widening to fit multiple lanes into limited right of way to reconstructing or expanding right of way. These varied conditions respond to both the latest design standards for some projects and trade-offs to achieve the best overall balance in others. Based on this feedback, the ability to finance and fund projects was heavily dictated by the overall approach, scope, environmental impacts, and land use impacts. Some projects included general-purpose capacity and related safety improvements as well as replacement of dated infrastructure. These combined attributes influenced the overall design approach—primarily whether to replace or widen the existing facility. Except for the I-35E and DFW Connector, which provided general-purpose capacity, most projects have tolled most or all of the added capacity as a matter of regional or state policy, and thus much of the project cost was for managed lanes. In some instances, these improvements preserved space for future general-purpose expansion.

Physical separation is one category where preferences to manage the speed differential was given emphasis. High-speed and large traffic volumes, coupled with a need to more easily enforce rules, have influenced emphasis on positive separation. Controlling access is another category. For reversible lanes, controlling access and managing potential wrong-way movements is intrinsic in the concept for safety reasons. For concurrent roadways, tolling can be simplified and reliability of roadway operations more assured. An incident in the general-purpose lanes is less likely to adversely impact the express lanes. However, attractiveness for using express lanes is tempered by ease in finding an entrance and exit that matches major travel patterns that are unique to each project setting. Cost also favors at-grade access designs. Fundamentally, the more open the access, the greater the potential financial return, but the harder the concept may be to manage and enforce. Access design has to balance these variables.

Table 6. Objectives for new construction of managed lanes.

Project/ Location	Add Capacity	Manage Added Capacity	Increase Vehicle Throughput	Ensure Reliability	Minimize Enforcement	Generate Revenue	Leverage Private Funding	Promote Transit Service	Promote Bus Rapid Transit	Handle Special Events
I-75/575 Atlanta	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
I-75 South Atlanta	Yes	Yes	Yes	Yes	Yes	Yes		Yes		Yes
I-635 LBJ Dallas	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
SH 183/I-820 Ft Worth	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
SH 114/121 Connector Dallas–Ft Worth	Yes	Yes	Yes	Yes	Yes	Some				
I-35E Dallas-Denton	Yes	Yes	Yes	Yes	Yes	Yes				
I-35W Ft Worth	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
SH 183 Extension Dallas	Yes	Yes	Yes	Yes	Yes	Yes				
I-405 Seattle	Yes	Yes	Yes	Yes		Yes		Yes		
SR 167 SB Extension Seattle	Yes	Yes	Yes	Yes		Yes				
I-15 San Diego	Yes	Yes	Yes	Yes				Yes	Yes	

Project design has been subjected to some changes in pricing policies associated with each region's experiences. Atlanta, Los Angles, and Seattle have all had to adjust their perspectives on how tolling can be used to manage demand, with trade-offs reflecting political concessions on toll caps. In such cases, signing and sign messages have been adjusted. Balancing demand resulted in access changes in Atlanta, while violations and public attitudes influenced removal of access restrictions on much of SR 167 in Seattle and, similarly, planned removal on southbound I-680 in the Bay Area.

Transferable Innovations

With an increasing number of states shifting urban policies toward pricing any new capacity, the design issues and value proposition posed by these managed lanes will likely be transferable to a number of project settings. In addition to the pricing innovations mentioned for conversions, other innovations found on some new construction projects include the following:

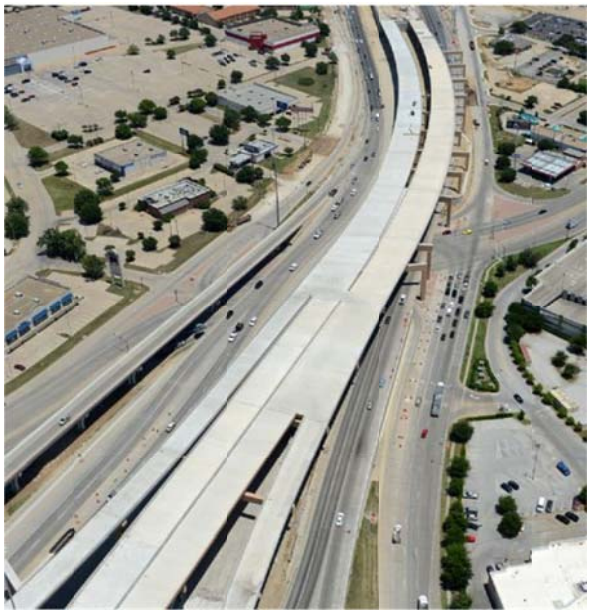
- **Partnering and delivery tools and approaches have changed.** Legislative tool authorization and policy tools to engage public-public and public-private dialog in design is perhaps the greatest transformative change to have occurred in managed lane practice on large-scale projects. Examples now abound to document how such

tools have changed practice and altered how design is undertaken, how risk is shared, and how delivery has been accelerated.

- **Assumptions for design life have changed.** At different ends of the spectrum, the value proposition to concessions and design-build toll facilities suggests that a much longer structural and pavement life is required for concessions stretching 50 to 70 years out. One concession planned for a 100-year structure life. At the other end of the spectrum are tolling and intelligent transportation system (ITS) infrastructures, which change almost yearly and certainly have a shorter life cycle than even current guidance may ascribe to.
- **Operational uncertainties drive innovation.** Adapting the design concept to be flexible to future operating conditions seems to be a fundamental departure from conventional freeway widening. Some projects such as I-15 in San Diego realized that their four-lane cross-section needed to consider potential peaks in demand that justified a moveable center barrier. Other strategies have focused on access flexibility by providing a uniform pavement section to support slip ramps anywhere through the buffer or physical separation. The I-110 project's uniform section provided an easy means to create weave lanes where a previous weave zone existed.
- **Going over (or under) everything is more common.** Concepts take new express lanes over existing freeway-to-freeway interchanges rather than attempting to negotiate columns and structures (see Figure 2 and Figure 3). This approach provides easier accommodation for direct connections, which duplicate ramps provided for general-purpose traffic. Such connections like those on I-75 in Atlanta or SH 183/I-820 in Ft. Worth are sometimes planned to connect directly to managed lanes on other intersecting routes. This approach creates a higher-profile interchange, which may create visual impact and push the footprint of the interchange ramps farther away, but it reduces costs and maintenance of traffic issues.

Source: North Tarrant Express

Figure 2. Flyovers from frontage roads.



Source: North Tarrant Express

Figure 3. Flyovers from elevated alignment over interchange.

- **Access equity is improved.** Direct-access treatments that offer connections for local traffic are rather new. Similar designs for HOV lanes were previously limited primarily to reaching major employment centers and serving transit service needs. By collecting demand for longer-distance trips directly to local arterials, collector-distributors, or frontage roads, weaves across GP lanes are reduced or eliminated. This approach to collection and distribution is being implemented on I-75/575 in Atlanta. Access equity is improved for local communities that otherwise would not benefit. Some projects like NTE in Dallas–Ft. Worth have extensive investments in direct local access ramps (see Figure 2 and Figure 3). These projects may improve overall traffic operation, or they may shift weaving and queuing to the frontage road and place more burden on arterial signal demand. Agencies are monitoring and weighing the pros and cons.
- **System signing and ITS capability are simplified.** Consolidation of signing, tolling, monitoring, and communication systems can be more easily made with new construction. These requirements can be designed into bridge structures and sign and toll gantries and facilitated as part of common backbone communication systems with better redundancies planned in. These attributes offer potential benefits to the customer experience and operators responsible for maintaining a reliable operation.

Gaps in Practice

The following gaps in practice were identified:

- **Access.** Clearer understanding and experience with different at-grade and direct (grade-separated) access is needed. A wide variety of concepts is being implemented and operated. There are pros and cons with each. Some justifications for a particular design are driven by stakeholder engagement and equity issues. System-level plans call for more direct-connection ramps, but the costs for these are often prohibitive. Performance monitoring will help inform these designs and design practice for future projects.
- **Maintaining reliability/response to incidents.** With higher volumes, the likelihood of incidents adversely affects operational reliability. Incorporation of physical separation can make accessing and responding to an incident harder than buffer separation. More cameras for monitoring are better than fewer, and this need was expressed by several developers. Off-the-shelf emergency gate designs to address this need have either been inappropriately specified or are in need of further refinement to meet all classes of design vehicles, including large emergency fire trucks that need to quickly access the express lanes or large commercial vehicles that may need to be evacuated. Recent gate applications on Dallas–Ft. Worth projects are proving to be undersized.
- **Performance.** While most new construction projects being implemented contain full breakdown shoulders, availability or lack of full shoulders on some single- and dual-lane designs may carry a higher safety risk and offsetting need for such investments and active traffic management. A need exists to better understand commensurate performance and reliability trade-offs.
- **Signing practice.** Signing consistency at a regional and national perspective is still a work in progress. Many new projects in the pipeline will increase likelihood of

inconsistencies and make retrofitting regional adopted practices more difficult. Efforts are needed to address a larger number of common signing and message needs in subsequent versions of the federal MUTCD.

- **Tolling.** Toll systems in each region have different approaches to transponder preferences and account management. This is already challenging within regions like Dallas–Ft. Worth and will become more so without more consistency in adopted practices.

Lessons Learned

In addition to the earlier list of lessons learned for conversion projects, following is a compilation of lessons learned from discussions held with design practitioners of new construction projects:

- **Financial feasibility is key.** Expect most aspects of a project concept to potentially change as a project is tested for financial feasibility. Integrating this aspect into the project team early minimizes this risk.
- **Scalability.** Project investments are scalable based on the intended life cycle and can be responsive to a determination of financial feasibility. A longer set of design-life assumptions for pavement and structures may justify a different set of financing assumptions that improve financial leveraging, and this is making costly managed lanes more viable for implementation.
- **Environmental risk.** Obtaining environmental evaluation and approval by the sponsoring agency, usually the state DOT, greatly simplifies the hand-off to a DB or P3 provider and reduces risk that is otherwise monetized at the proposal.
- **Outreach.** Political and public engagement will be a need for extensive and ongoing outreach through and beyond project opening.
- **Multimodal opportunities.** Ideally, a project provides benefits to all users and potentially other modes like transit. San Diego's I-15 corridor offers a good example.
- **Regional policies.** Creation and adoption of policies supporting project development are good to a point for consistency and guidance, but too much policy can potentially hamstring flexibility needed in the evolving project design, operation, and procurement process.
- **Partnering.** Having more partner perspectives often leads to better, sounder designs. Both public and private partners can play a big role in authoring the design, particularly in the early stages of procurement. Allow the industry to get involved and suggest ideas. The public agencies have formalized this through requests for information. One interview respondent provided this comment:

  > *Sometimes private industry tried to "set the hook." Sometimes you have to take input with a grain of salt. One proposer said ours was a great project and fully fundable, but their plan called for toll gates throughout. Toll gates would have been an operational problem for [the state DOT].*

- **Access equity.** Minimizing access for a facility serving longer-distance trips is difficult. Local communities want more, not less. To be successful, the project needs to provide a legitimate trip with legitimate time savings, so there is a need to minimize access.

- **Keep it simple.** Simple operational rules (e.g., giving fewer groups special waiver from tolls) make enforcement practice and design provisions easier to address through standard design for new construction projects.
- **Maintenance of traffic.** Testing constructability by preserving travel lanes will be a key factor in determining the design approach. Keeping the same number of general-purpose lanes open during construction may be required to limit impacts.
- **Consistency.** Planning and developing a system versus testing and demonstrating designs first may take longer but can lead to a more consistent application.

DIRECTION FOR USING FINDINGS

This chapter offers an overall perspective of what has been learned from the representative case studies. It also provides an initial overview of how these experiences may be considered within the current draft of the NCHRP 15-49 *Guidelines for Implementing Managed Lanes* (*1*).

Project Context

Many areas are simultaneously and successfully implementing managed lanes in two broad categories, termed conversions and new construction in this synthesis. The case studies provide details of how each type of project is being facilitated.

Conversions have almost universally focused on improving management of an existing asset—adding tolling to regain lost reliability or expand potential utilization. These conversion changes are implemented for a near-term operation horizon. This perspective has many parallels within a state DOT that addresses improved freeway corridor management through many approaches. However, practitioner experiences suggest much more evaluation effort and internal/external angst is occurring to move conversions forward. This frustration in some locales is costly and adversely affecting the ability to implement conversions. Some means of clarifying, simplifying, and supporting tenets that carry forth guidance in evaluating and implementing conversions would be of value in the guide.

New construction easily fits into the project development context of any highway facility, so guidance from a number of resources captures implementation attributes. Case studies for new construction can help build an understanding of how managed lane designs are being implemented.

Suggestion

While many attributes are similar to both conversions and new construction, such as agency partnering, evaluation of design trade-offs for constrained settings, and performance requirements, differences are equally apparent. These differences represent perspectives that support the design and project development practices being implemented. Some differences are noteworthy and informative but outside the purview of implementation guidance. For example:

- The role of P3 concession engagement requires a minimal threshold of cost to justify the concession's interest, and most conversions fall below this.

- Some projects have one sponsor, while others have two or more, regardless of whether they are conversions or new construction. Partnering has appeared to enhance more complex projects or projects in complex settings.
- Some agencies have distinct policies to carry out a managed lane program, and others do not; in both cases, they arrive at an equally appropriate point where their managed lanes have been woven into an effective system.

Other experiences gained from practitioner interviews can strengthen the current draft guide by both identifying current guidance shortcomings from prior resources and posing challenges to the research team in developing guidance that can address where current thinking is at on selected topics. Some examples include the following:

- Practitioners are now embracing buffer widths of less than 4 ft, and in one case considering adoption of a local 2-ft preference.
- At-grade access preferences for concurrent lanes are expanding from a more restricted design setting to include a more open-access concept, at least for single-lane treatments.
- Access equity with adjoining, affected communities is a new concept that has received little attention but been given more credence for selected projects than has been previously reported.
- Evaluation tools commonly referenced for traffic analyses, including simulations, have performed poorly in helping agencies isolate and attempt to mitigate conversion impacts in hyper-congested corridors.

If these examples were isolated and not likely to be applicable or transferable to the wider audience of practitioners, then they would not be beneficial to include. However, for many experiences, these topics may resonate to a wide audience.

What this study has uncovered is that within the design and implementation topics discussed, there are unique practices and issues that could be considered for various chapters of the guide (*1*). Practitioners were extremely candid with their feedback, and in doing so offered useful experiences in how decisions are made. In almost every topic contained in the guide, there are practitioner-informed ideas, useful rules of thumb, and experiences that may help make the guide more practitioner-centric, and thus useful as an application reference. Many ideas will likely generate further research needs and wider data gathering among the larger project and practitioner network.

CHAPTER 3

DIMENSIONS WITHIN MANAGED LANE ENVELOPES

INTRODUCTION

The 2004 AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*) includes a trade-off analysis on various design options for reducing width from recommended dimensions. The 2004 AASHTO HOV guide provides suggested priorities of cross-section adjustments to be made to a facility's design. In the time since publication, additional operational strategies for MLs have emerged, including the use of pricing to meter traffic, dynamic shoulder lanes, active lane control signals coupled with variable speed limits, and reduced lane widths in order to accommodate new managed lane facilities. In the state-of-the-practice review in Phase I of the 15-49 project, practitioners expressed a desire for more definitive guidance regarding designing managed lanes in constrained conditions, including an analysis of trade-offs between buffer widths (or exclusion thereof), shoulders, and travel lanes. These components prescribed to the operation of the managed lane are called the managed lane envelope in this research.

This chapter presents the methodology and findings from two Phase II studies. Study 5R.3 gathered managed lane practitioner information on the trade-offs considered when making cross-section width decisions and reviewed this information using focus groups. Study 5R.2 identified the relationship as revealed through travel data between operations and cross-section width, including the type of buffer design separating the managed lanes from the general-purpose lanes. Key measures believed to be affected by lane, shoulder, and buffer widths are operating speed and lateral position since drivers may adjust their speed or position in the managed lane depending on their proximity to a concrete barrier or adjacent general-purpose lane. The findings from 5R.3 and 5R.2, along with findings from the literature, were used to develop suggestions for the managed lanes guidance developed to date.

OBJECTIVE

The objectives of Study 5R.2 were to collect speed and lateral position data on existing managed lane facilities with a range of lane widths, shoulder widths, and buffer widths within both tangent and horizontal curves and identify potential relationships between the geometric design element values and the measures of effectiveness.

The objective of Study 5R.3 was to gain an understanding of how design trade-off decisions and prioritization are being made by practitioners on managed lane projects. Through this effort, the research team determined the priorities of managed lane practitioners in making decisions on lane width, shoulder width, and buffer width.

The findings from both studies were used to develop updated guidance to help practitioners determine a priority order of adjustments. The list of adjustments was developed based on observations and practical considerations.

The documentation of these studies provides insight into the cross-section decisions that are being made today by managed lane practitioners for trade-offs. In turn, the developers of new managed lane facilities may gain insight into how their conditions could be assessed in light of current practice.

RESEARCH METHODOLOGY

The research approach was divided into the following activities:

- **Compilation of existing practices**—Researchers reviewed the literature, manuals, and guidance documents to summarize the available guidance and supporting information on this specific topic. For example, the trade-off examples in the 2004 AASHTO HOV guidelines tend to reduce the distance to the median barrier first, followed by the general-purpose shoulders and then the HOV lane width. Other practices recommend a different order of adjustments based on different priorities. These practices are presented in the Existing Practice section and were used to develop specific questions to ask practitioners, as reported in the section entitled Managed Lane Practitioners Focus Group 1.
- **Survey of applied methods by practitioners**—An online-based survey was developed in order to seed conversation on potential measures of effectiveness (e.g., operating speed) that could be affected by the combination of lane width, shoulder width, and buffer width. The survey asked practitioners of all operational and under-construction managed lanes (as of January 2015) which measures of effectiveness (MOEs) their organization optimizes when faced with a decision to favor one MOE over another and what steps the organization takes to accomplish the MOE by adjusting the three design elements under consideration.
- **Observation and documentation of current conditions**—The research team obtained measurements for lane, shoulder, and buffer widths on a selection of facilities. The availability of aerial photographs was a critical advantage in permitting the collection of extensive geometric data without costly site visits. With the design details for a sample of managed lane facilities, researchers selected a portion to visit in person or to use fixed video cameras, either from a traffic management center (TMC) or placed by a research team member, to collect lateral position data. Sites were chosen based on geographic distribution and variety in design widths. The research team collected data in five regions (Los Angeles, San Francisco/Oakland, Minneapolis/St. Paul, Dallas Metroplex, and Houston) with the number of locations within those regions depending on the distance between facilities or number of sites provided by the local agency. Several data collection methods were used including (a) video from TMC cameras, (b) video from installed cameras, and (c) data collected in an instrumented vehicle outfitted with appropriate sensors and video recorders. For the sites where data were collected with an instrumented vehicle, researchers collected data on speed and lateral position of vehicles that use the managed lanes. For the sites with fixed video cameras, the lateral position of vehicles in the managed lanes was recorded. Figure 4 illustrates the left lateral position (LP-Lf) and the right lateral position (LP-Rt) for a vehicle in a managed lane. The lateral position and available speed data were compared to the shoulder, lane, and buffer dimensions to identify potential relationships.

Source: TTI

Figure 4. Example of right and left lateral position for vehicle near center of the managed lane.

- **Discussion with practitioners**—Detailed discussion with a subset of responding practitioners was conducted as an online-based focus group. The initial session presented findings from the compilation of practice and practitioner survey and discussed additional components necessary for understanding agency desires for conducting trade-off analysis. An additional session, held July 22, 2015, reviewed research findings from the companion research study and explored potential recommendations for design trade-offs based on agency preferences in consideration of the research.
- **Application of field and focus group data along with findings from the literature to current practice**—The findings from both studies along with findings from the literature were used to develop guidance for shoulder, lane, and buffer widths.

EXISTING PRACTICE

Introduction

An analysis of guidelines for changes in lane, shoulder, and buffer widths was undertaken to provide a starting point for discussions. This analysis is a representative sampling of state and national criteria but is not presented as an exhaustive list of state and federal guidelines.

Guidelines from AASHTO (*3*) and the state DOTs of Nevada (*4*), California (*5*), and Washington State (*6*) were reviewed. Also, Texas was reviewed to the extent that it was determined that it relies on AASHTO standards. The states reviewed were based on the states being identified as having relatively significant managed lane guidelines. While AASHTO

standards were not specifically adopted by the states reviewed, there were numerous similarities between AASHTO and state guidance. No attempt was made to determine whether AASHTO impacted state guidance or whether state guidance impacted AASHTO. A significant amount of experience and information sharing occurred on this subject within the industry.

Overview

The recommended reduction in widths to accommodate a less-than-ideal cross-section to allow the deployment of managed lanes is dependent on the type of envelope where the cross-section is contained (i.e., concrete barrier-separated, reversible, contiguous, etc.). It is possible to summarize, in general, width reduction guidelines because they tend to follow a predictable pattern in almost all cases.

The left (inside) shoulder tends to be the first reduction, for AASHTO and other state guidance, in many cases to a minimum of 2 ft. It should be noted that this reduction can be problematic if a concrete barrier is to the left of the shoulder. In curves to the left, sight distance diminished by the narrow shoulder can become an issue and should be considered in the design of the specific facility.

For non-barrier-separated managed lanes, the outside shoulder is to the right of the rightmost general-purpose lane, hereafter referred to as the right (outside) shoulder. It should be noted that AASHTO does not expressly identify trade-offs for buffer widths, but this is addressed in Caltrans and other state guidance. After reducing the inside shoulder, the next approach identified by AASHTO and other state resources is to reduce the outside shoulder, but the reduction is usually not severe, with 8 ft being a common minimum. This clearly reflects a desire to maintain a refuge space where it is practical. Reduction below an 8-ft width may be considered by some agencies over a relatively short distance, for instance, when legacy bridge piers impinge upon shoulders in an underpass.

The lane widths in the managed lane portion of the facility are often the next issue addressed, being reduced from 12 ft to 11 ft. No agency examined recommends lane widths below 11 ft. It should also be noted that this reduction is dependent on the vehicle type allowed to access the managed lane facility. A reduction may not be appropriate when trucks and other large vehicles are allowed in the managed lanes (as is the case in Colorado and Texas).

Consideration may also be given to reduction in the width of general-purpose lanes. This is again from 12 ft to 11 ft. However, many agencies suggest/require that the right (outer) lane remain at 12 ft to accommodate large vehicles.

Some situations have a right shoulder that was further reduced from 8 ft due to other appropriate reasons. AASHTO, as discussed below, recommends a minimum of 4 ft. As a practical matter, this may depend on the type of facility being contemplated. For instance, in a barrier-separated facility, reduction of both the inside and the outside shoulder within the barrier may be reasonable if there is sufficient room for traffic to still pass a disabled vehicle, even if that vehicle needs to encroach to some extent into a travel lane due to the reduced

shoulder. In this case, travel speeds would, of course, be significantly reduced. The number and distance between access points might also be an issue in this decision. If intermediate access points exist so the traffic can be diverted from the managed facility in the event of a stalled vehicle or crash, it could be reasonable to consider shoulders that were narrower than would exist on a facility that only had one entrance and one exit.

It is also possible to gain a small amount of additional room by converting the barrier face from a sloped face to a vertical face. This might be an especially appropriate treatment in exceptionally confined spaces such as a freeway underpass with bridge pier impingement.

The provision of enforcement areas, especially within and immediately after toll zones, is a recommended practice for providing adequate monitoring for managed lane facilities. Sufficient width is required to allow storage of the vehicles in the enforcement area, along with additional width to allow enforcement officers, emergency responders, and others to walk outside their vehicles without having to enter the adjacent travel lane. Caltrans calls for a 23-ft width for its median enforcement areas, although this is reduced in some conditions. Pullouts must also be designed with sufficient length to allow vehicles to enter and exit while changing speeds from freeway speeds to a stop condition and back again. Caltrans and WSDOT guidelines have lengths of 1300 ft for their enforcement pullouts (minimum of 1000 ft) in addition to the entry and exit taper lengths.

AASHTO

AASHTO has a longstanding leadership role in the development of roadway design standards including those reflected in the AASHTO *Policy on Geometric Design of Highways and Streets* (commonly known as the *Green Book*) (*7*). Development of design guidance for HOV lanes continues that leadership. Information for AASHTO guidance is available in the *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*). AASHTO provides guidance for three different types of managed lanes. In some cases, minimum recommended dimensions are given, and in other cases, specific dimensions are provided. The AASHTO HOV guidelines (*3*) include a trade-off analysis on various design options for reducing width from recommended dimensions. Tables 3-3, 3-7, and 3-8 of the AASHTO guidelines provide suggested priorities of cross-section adjustments to be made to facility design (see examples reproduced in Table 7, Table 8, and Table 9).

Table 7. AASHTO—example of prioritized list of design trade-offs for two-way barrier-separated HOV lane facilities.

Ordered Sequence	Cross-Section Design Change
First	Reduce HOV envelope to 12.6 m (42 ft) according to the middle schematic of Figure 3-3 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 trade-offs 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: A formal design exception request may need to be processed to document the design change. The ordered sequence presented here is only an example list. Some states may prefer a difference sequence.
Source: Adapted from Table 3-3 in *Guide for High-Occupancy Vehicle (HOV) Facilities*, 2004, by the American Association of State Highway and Transportation Officials (*3*).

Table 8. AASHTO—example of prioritized list of design trade-offs for buffer-separated, concurrent-flow HOV lane facilities.

Ordered Sequence	Cross-Section Design Change
First	Reduce HOV envelope to 11.4 m (38 ft) according to Figure 3-13.
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 trade-offs 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. The designer must also consider the design exception requirements.
Source: Adapted from Table 3-7 in *Guide for High-Occupancy Vehicle (HOV) Facilities*, 2004, by the American Association of State Highway and Transportation Officials (*3*).

Table 9. AASHTO—example of prioritized list of design trade-offs for non-separated, concurrent-flow HOV lane facilities.

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) according to Figure 3-14.
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 trade-offs 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. The designer must also consider the design exception requirements.
Source: Adapted from Table 3-8 in *Guide for High-Occupancy Vehicle (HOV) Facilities*, 2004, by the American Association of State Highway and Transportation Officials (*3*).

Nevada Department of Transportation

Nevada (*4*) has a six-step sequence that closely mirrors AASHTO guidance. Recently updated in 2013, Nevada DOT (NDOT) guidelines address contiguous concurrent-flow and barrier-separated concurrent-flow managed lane facilities; however, it should be noted that Nevada does not address buffer separation between HOV and general-purpose lanes. It should also be noted that Nevada does not provide for reduction of the right shoulder below 8 ft.

NDOT (*4*) advises that, particularly for retrofit facilities, trade-offs and accommodations may need to be made to applicable guidelines for affected design elements (e.g., lane width, shoulder width, lateral clearance). If so, a design exception may need to be completed to construct a facility that incorporates such trade-offs. An example of a series of possible trade-offs for designing the cross-section for a concurrent-flow lane is shown in Table 10. NDOT notes that this list is provided as an example and is not intended to supersede competent engineering judgment in specific design applications.

Table 10. NDOT—trade-offs for contiguous concurrent-flow lanes.

Suggested Sequence	Cross-Section Design Change
1	Reduce the 14-ft median shoulder (for continuous enforcement) to no less than the desirable criteria as per NDOT Standard Plans for Road and Bridge Construction (NDOT Standard Plans). Provide designated enforcement areas instead.
2	Reduce the median shoulder to the minimum criteria as per NDOT Standard Plans.
3	Reduce the outside (right) shoulder to typical minimum width as per NDOT Standard Plans.
4	Reduce median shoulder to 2 ft.*
5	Reduce the managed lane to 11 ft.*
6	Reduce the general-purpose lanes to 11 ft, starting from the left and moving to the right as needed. The outside (right) lane is to remain at 12 ft.*
7	Transition barrier shape at columns to vertical face.

Source: Adapted from NDOT Design Manual, Table 1-1 (*4*).

* Requires design exception.

California Department of Transportation (Caltrans)

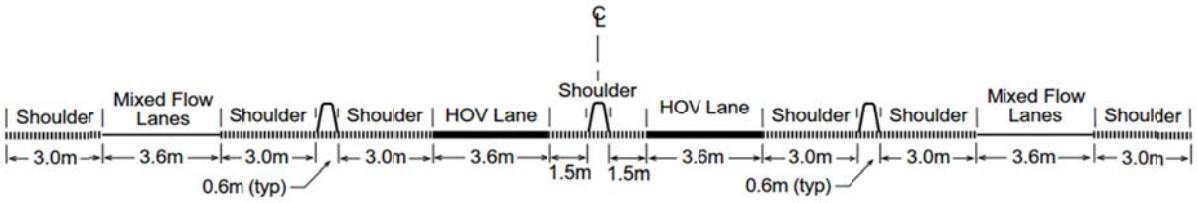
Guidance from Caltrans (5) provides perhaps the most specific direction of the representative guidance reviewed. Specific guidance is given for four facility types, and the majority of guidance provides very specific requirements.

Two-Way Barrier-Separated HOV Facilities

Two-way barrier-separated facility criteria are shown Figure 5. While it may at first glance seem that relatively little guidance is given for this type of facility, the lack of guidance is an indication that this type of facility requires a wider cross-section versus other facility types considered by Caltrans. This is a good example that design options are often available if there is sufficient flexibility to meet the purpose that the managed lane is intended to achieve. If the presented minimums cannot be met, a decision to consider a different type of facility is recommended. Specific reduction suggestions are:

- First, reduce the left HOV shoulder to 0.6 m (2 ft).
- Second, reduce the HOV lane to 3.3 m (11 ft).

If the above reductions are not sufficient to meet right-of-way constraints, then buffer-separated or contiguous HOV facilities should be considered.



Source: Adapted from Figure 3.1 (5)

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Figure 5. Caltrans—Two-way barrier-separated HOV facilities.

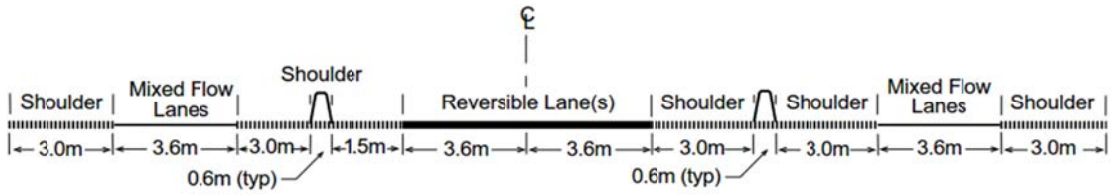
Reversible Barrier-Separated HOV Facilities

Caltrans's reversible barrier-separated HOV facilities (see Figure 6) have many more options for width reduction than its two-way counterparts. This reflects the fact that the decision to use a reversible lane often indicates that a two-way facility is not practical. It should also be noted that the total shoulder width within the reversible envelope is sufficient to allow passage even with a disabled vehicle on one of the shoulders. In addition, the guidance reflects the practice of providing a wider shoulder on one side of the reversible lanes rather than two shoulders of equal width, which minimizes the possibility that a disabled vehicle will

encroach into the travel lanes themselves, as would be the case if two equal shoulders are used.

The general-purpose (mixed-flow) lanes follow the pattern of reducing lane width from the left (inside) of the facility to the right (outside) of the facility with the right general-purpose lane remaining at 12 ft to accommodate large vehicles. Specific Caltrans reduction suggestions are:

- First, reduce the 1.5 m (5 ft) HOV shoulder to a minimum of 0.6 m (2 ft) while maintaining a minimum 3.0 m (10 ft) shoulder on the other side.
- Second, reduce the HOV lanes to a minimum of 3.3 m (11 ft).
- Third, reduce the mixed-flow left shoulder to a minimum of 2.4 m (8 ft), if the shoulder is structurally adequate.
- Fourth, reduce the mixed-flow lanes to 3.3 m (11 ft), starting with the left lane and moving to the right as needed. The outside mixed-flow lane should remain at 3.6 m (12 ft) unless truck volumes are less than 3 percent.
- Fifth, reduce the left shoulder for the mixed-flow lanes to a minimum of 0.6 m (2 ft). Shoulders less than 2.4 m (8 ft) but greater than 1.5 m (5 ft) are not recommended. Any excess width resulting from a reduction of median shoulder width from 3.0 m (10 ft) to 1.5 m (5 ft) or less should be used to restore the mixed-flow lane widths to 3.6 m (12 ft) starting from the outside and moving to the left.



Source: Adapted from Figure 3.1 (5)

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Figure 6. Caltrans—Reversible barrier-separated HOV facility.

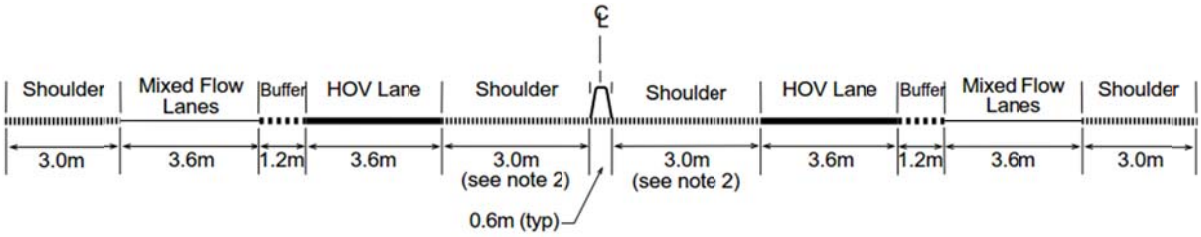
Buffer-Separated HOV Facilities

The Caltrans guidance for buffer-separated HOV facilities is notable for its reference to the buffer width, as well as its reference to enforcement. As shown in Figure 7, 14-ft median shoulders are the preferred cross-section. As discussed within the Caltrans document, this is solely to accommodate continuous enforcement of the lanes. Reduction of the inside shoulder to 10 ft is appropriately the first recommended reduction of the cross-section, but the need for coordination with law enforcement to develop effective enforcement areas is particularly noteworthy.

The seventh reduction criterion also deserves particular attention. Any shoulder greater than 5 ft can appear to a driver to allow the vehicle to completely move into the shoulder, and this is certainly not the case. It is likely that this is the reason Caltrans recommends that shoulders over 5 ft that cannot be developed to a full 8 ft not be used, and lane widths increased instead. The ordered list of reduction criteria is as follows:

- First, reduce the median shoulders from 4.2 m (14 ft; the width to accommodate continuous enforcement areas) to 3.0 m (10 ft). Any reduction of the median shoulders should be accompanied by the addition of California Highway Patrol (CHP) enforcement areas.
- Second, reduce the buffer to 0.6 m (2 ft).
- Third, reduce the median shoulders to a minimum of 2.4 m (8 ft).
- Fourth, reduce the HOV lane to 3.3 m (11 ft).
- Fifth, reduce the number-one mixed-flow lane to 3.3 m (11 ft).
- Sixth, reduce the remaining mixed-flow lanes to 3.3 m (11 ft), starting with the number-two lane and moving to the right as needed. The outside mixed-flow lane should remain at 3.6 m (12 ft) unless truck volume is less than 3 percent.
- Seventh, reduce the median shoulders to a minimum of 0.6 m (2 ft). Shoulders less than 2.4 m (8 ft) but greater than 1.5 m (5 ft) are not recommended. Any excess width resulting from a reduction of median shoulder width from 2.4 m (8 ft) to 1.5 m (5 ft) or less should be used to restore the mixed-flow lane widths to 3.6 m (12 ft) starting from the outside and moving to the left.

The reduction of the median shoulders from 4.2 m (14 ft) to either 2.4 m (8 ft) or 0.6 m (2 ft) should be combined with the construction of enforcement areas.



Source: Adapted from Figure 3.2 (5)

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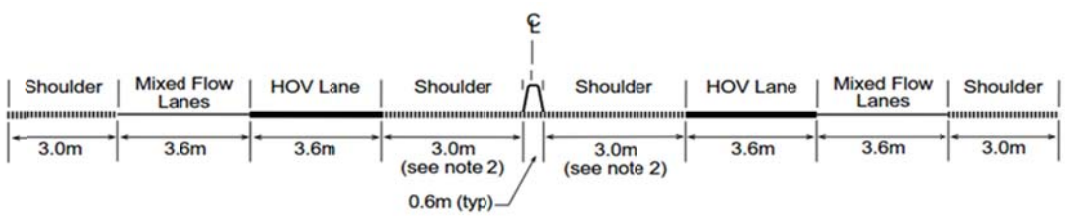
Figure 7. Caltrans—Buffer-separated HOV facility.

Contiguous HOV Facilities

The Caltrans guidance for contiguous HOV facilities contains most of the issues previously discussed for other types of facilities. Their graphic is shown in Figure 8. As with other facility types, issues related to enforcement and shoulder width must be taken into account. The ordered list of reduction criteria is as follows:

- First, reduce the median shoulders from 4.2 m (14 ft; the width to accommodate continuous enforcement areas) to 3.0 m (10 ft). Any reduction of the median shoulders should be accompanied by the addition of CHP enforcement areas.
- Second, reduce the median shoulders to a minimum of 2.4 m (8 ft).
- Third, reduce the HOV lane to 3.3 m (11 ft).
- Fourth, reduce the mixed-flow lanes to 3.3 m (11 ft), starting with the left lane and moving to the right as needed. The outside mixed-flow lane should remain at 3.6 m (12 ft) unless truck volumes are less than 3 percent.
- Fifth, reduce the median shoulders to a minimum of 0.6 m (2 ft). Shoulders less than 2.4 m (8 ft) but greater than 1.5 m (5 ft) are not recommended. Any excess width resulting from a reduction of median shoulder width from 2.4 m (8 ft) to 1.5 m (5 ft) or less should be used to restore the mixed-flow lane widths to 3.6 m (12 ft) starting from the outside and moving to the left.



Source: Adapted from Figure 3.2 (*5*)

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Figure 8. Caltrans—Contiguous HOV facility.

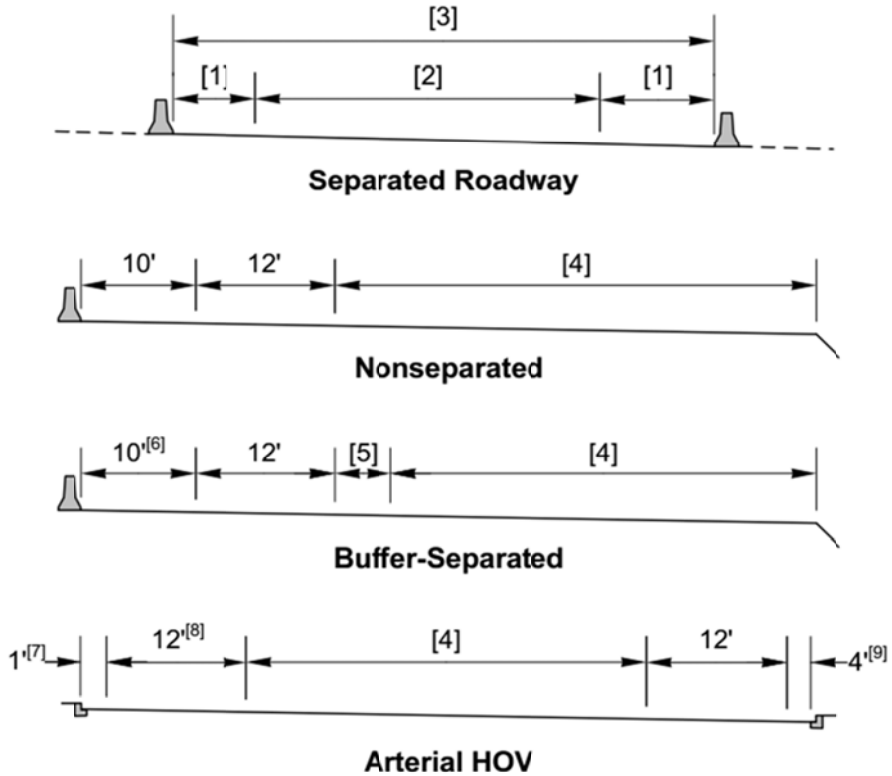
Washington State Department of Transportation

WSDOT (*6*) provides guidance on four separate types of managed lanes, including arterial facilities (see Figure 9). Some guidance provides specific measurements, and other guidance is dependent on issues such as functional class and number of lanes. Guidance provided in the WSDOT *Design Manual* concisely describes the design options available, with frequent reference to other portions of the design manual within the guidelines. This encourages consistency among its various types of facilities, whether managed or not. Also, as shown in the first note in Figure 9, WSDOT indicates the desirability of one larger shoulder and one smaller shoulder versus two average shoulders.

Summary

The relatively consistent approach between agencies to reducing lane, shoulder, and buffer widths in less-than-ideal cross-sections shows an important exchange of information between transportation agencies to the significant benefit of the traveling public. Not only does this consistency show that significant efforts are being made to adopt and disseminate best

practices, it also bodes well for driver expectancy since standards are very likely to be similar from state to state. While additional information on operational efficiency and safety still needs to be gathered to allow further analysis of specific recommendations, the existing strategies and criteria that have been developed by various states and AASHTO provide this foundation.



Notes:

[1] The sum of the two shoulders is 12 ft for one-lane and 14 ft for two-lane facilities. Provide one shoulder with a width of at least 10 ft for disabled vehicles. The wider shoulder may be on the left or the right. Maintain the wide shoulder on the same side throughout the facility (see 1410.06(4)(a)2).

[2] 12-ft minimum for single lane, 24-ft minimum for two lanes. Wider width is required on curves (see 1410.06(4)(a)1 and Exhibit 1410-1).

[3] For total width requirements, see 1410.06(4)(a)3.

[4] Width as required for the design level, functional class, and the number of lanes.

[5] Buffer 2 to 4 ft or 10 ft or more.

[6] When buffer width is 4 ft or more, may be reduced to 8 ft.

[7] 2 ft when adjacent to concrete barrier.

[8] Arterial HOV lanes on the left operate in the same direction as the adjacent general-purpose lane.

[9] May be reduced to 2 ft with justification.

Source: Adapted from *WSDOT Design Manual* Exhibit 1410-2 (*6*), Washington State Department of Transportation

Figure 9. WSDOT—HOV design guidance.

SURVEY OF PRACTICE

An online survey of managed lane practitioners was conducted in order to identify existing practice and established procedures as they pertain to applying trade-offs in managed lane design. The intent of the survey was to articulate applied practice, with opinion and evaluation of those procedures reserved for the focus group dialog, which will be summarized in the following section.

Methodology

The primary source of information was drawn from practitioners who had close knowledge of or were instrumental in the design decision-making process. Practitioners were defined as any person currently serving in a public agency who was engaged in managed lane design and was also likely to influence the design outcome. Participating practitioners have served in various disciplines as they pertain to design decisions. Furthermore, some practitioners were not involved in initial project design but have been actively engaged in evaluating and implementing cross-section alternatives in reaction to observed traffic and safety issues.

Invited organizations included:

- State DOTs:
    - California.
    - Colorado.
    - Florida.
    - Georgia.
    - Minnesota.
    - Texas.
    - Utah.
    - Virginia.
    - Washington.
- Regional transportation agencies (including toll and county-based agencies):
    - Alameda County Transportation Commission (California).
    - Camino Real Regional Mobility Authority (Texas).
    - Central Texas Regional Mobility Authority (Texas).
    - Harris County Toll Road Authority (Texas).
    - Los Angeles County Metropolitan Transportation Authority (California).
    - Miami Dade Expressway Authority (Florida).
    - Orange County Transportation Authority (California).
    - Riverside County Transportation Commission (California).
    - San Bernardino Associated Governments (California).
    - Santa Clara Valley Transportation Authority (California).
    - Solano Transportation Authority (California).
    - State Road and Toll Authority (Georgia).
    - Tampa Hillsborough Expressway Authority (Florida).
- Metropolitan planning organizations:
    - Metropolitan Transportation Commission (California).
    - San Diego Association of Governments (California).

- Transit agencies:
    - Houston METRO (Texas).

State DOTs often included both a headquarters perspective and local district (region) perspectives. As such, state DOTs were represented by multiple individuals in both the survey and dialog activities.

The survey was conducted online in February 2015. Invitations for the survey were submitted by email only to the participants identified through the process described above, and completion of the survey was limited to only those invited by email.

Survey Results

Organizational and Respondent Demographics

A total of 21 organizations responded to the invitation, reflecting a representative sample of all managed lane facilities either in operation or under construction in early 2015. The roles served by responding individuals represented a range of disciplines, as shown in Table 11. Half of respondents indicated a primary role in facility design, with most indicating multiple roles in developing and operating managed lane facilities. When asked how many years of experience each respondent had with managed lanes, the average response was 12 years, with a minimum of 3 years and maximum of 35 years.

Respondents reflected all stages of project development—from initial planning activities through operations, as shown in Table 11. As a result, respondents to the survey had the opportunity to reflect on design guidance from multiple perspectives—from initial study, to physical design, through evaluation of performance.

Typical Cross-Section

Survey respondents addressed multiple questions pertaining to the typical cross-section of their managed lane facilities. All forms of managed lanes, including reversible-flow, concurrent-flow, and ramp-based managed lanes, were present in respondents' facilities, as shown in Table 11.

For concurrent- and reversible-flow facilities, respondents provided the typical shoulder, lane, and buffer widths for each type. Each component of the cross-section was reflected, including cross-section on dual-lane concurrent-flow facilities with transition lane. This yielded the following articulation of average, minimum, and maximum widths for each component.

As shown in Table 12, variation on concurrent-flow facilities can be viewed as being relatively high for shoulder and buffer widths. The full range of AASHTO-articulated trade-offs is present in the data, including reductions to 11-ft widths for both managed lanes and general-purpose lanes. This reflects the different environments in which the managed lanes were implemented, including constrained environments and use of shoulders as travel lanes. In comparison, reversible lanes are often implemented in environments that permit higher

design standards in lieu of additional bi-directional capacity. As shown in Table 13, general-purpose and managed lane widths have generally remained 12-ft wide. However, shoulders within the reversible facility, in some cases, have been narrowed substantially.

Table 11. Survey results.

Question	Answers	Frequency
Participants' roles within their organizations	Design—roadway	10
	Management/administration	10
	Project management	8
	Planning	7
	Policy	7
	Operations	6
	Design—technology	4
	Alternative delivery	3
	Design—structures	2
	Other	1
	Legal[a]	0
	Financial/accounting[a]	0
Current managed lane activity by organization	Implementation/construction	19
	Design (e.g., PS&E or final design)	18
	Planning (e.g., feasibility study)	15
	Environmental (e.g., planning and environmental linkage, environmental assessment, or environmental impact statement)	15
	Operations	14
	Identified, but not formally studied yet	3
Type of managed lane currently deployed	Concurrent flow (single lane in each direction)	19
	Concurrent flow (two or more lanes in each direction)	14
	Direct connector ramp	13
	Reversible flow (barrier-separated)	7
	Ramp queue bypasses	6

[a] Option was provided in the survey instrument, but no respondent selected this option.

Table 12. Reported lane and shoulder widths for concurrent-flow facilities.

Measure	ML_S	ML#1	ML#2	ML#3	Buf	GP#1	GP#2	GP#3	GP#4	GP#5	GP_S
Average	8.1	11.6	11.9	11.5	3.1	11.7	11.8	11.8	11.9	12.0	10.3
Minimum	2.0	11.0	11.0	11.0	0.0	11.0	11.0	11.0	11.0	12.0	8.0
Maximum	10.0	12.0	12.0	12.0	5.0	12.0	12.0	12.0	12.0	12.0	12.0
Responses	15	15	9	2	16	16	16	14	9	3	16

Note: Column headings:

- Measure = average, minimum, or maximum of geometric feature or number of respondents providing information.
- ML_S = width of managed lane left shoulder (ft).
- ML#X = width of managed lane, where X = 1, 2, or 3 (ft).
- Buf = width of buffer (ft).
- GP#X = width of general-purpose lane, where X = 1, 2, 3, 4, and 5 (ft).
- GP_S = width of right shoulder (ft).

Table 13. Reported lane and shoulder widths for reversible facilities.

Measure	ML_ LS	ML #1	ML #2	ML #3	ML _RS	B	GP_ LS	GP# 1	GP# 2	GP# 3	GP# 4	GP# 5	GP_ RS
Average	9.3	11.8	11.8	12.0	8.8	-	8.0	12.0	12.0	12.0	12.0	12.0	11.2
Minimum	4.0	11.0	11.0	12.0	4.0	-	4.0	12.0	12.0	12.0	12.0	12.0	10.0
Maximum	12.0	12.0	12.0	12.0	12.0	-	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Responses	6	6	6	2	6	-	5	5	5	4	3	1	5

Note: Column headings:

- Measure = average, minimum, or maximum of geometric feature or number of respondents providing information.
- ML_LS = width of managed lane left shoulder (ft).
- ML#X = width of managed lane, where X = 1, 2, or 3 (ft).
- ML_RS = width of managed lane right shoulder (ft).
- B = Barrier, space provided in table to demonstrate that a concrete barrier separates the managed lane from the general-purpose lanes.
- GP_LS = width of general-purpose left shoulder (ft).
- GP#X = width of general-purpose lane, where X = 1, 2, 3, 4, and 5 (ft).
- GP_RS = width of general-purpose right shoulder (ft).

Commentary was offered by respondents regarding the nature of deviations from the typical cross-section. These deviations include:

- Shoulders and buffer are reduced to 2 ft in certain cases with severe geometric restrictions.
- Lanes are reduced to 11 ft where the third managed lane is added as a weave lane for ingress and egress.
- Depending on the unique goals of the project in the corridor and the financial constraints, retrofitted managed lane typical cross-sections reduce inside shoulder to approximately 2 ft.
- Travel lanes are reduced to 11 ft. For heavy truck corridors, the two outside lanes are held at 12 ft.
- In many locations, the median shoulder is less than the 10-ft standard. It may be as little as 2 ft.
- Lane widths, buffer widths, and shoulders are mostly minimum design standard widths, with even further narrowing down to almost zero, with design exceptions being granted at constricted points.

For making width trade-off decisions, respondents indicated they rely most commonly on state-based managed lane design guidance, AASHTO guidelines, and engineering judgment, as shown in Table 14. It should be noted that federal and AASHTO influence may be present in developing state guidance, so these are not mutually exclusive.

Table 14. Survey results.

Question	Answers	Frequency
How are widths of shoulders, lanes, and buffers determined?	State-based HOV or managed lane design guidance	13
	Engineering judgment	11
	AASHTO HOV guide	8
	FHWA *Priced Managed Lane Guide*	7
	Other	5
	Other state-based design guidance (outside home state)	3
	Academic-based design guidance	2
	Local-based HOV or managed lanes design guidance	0

When asked to describe the primary factors involved for design trade-offs, respondents offered the following factors:

- Lane, shoulder, and buffer width factors:
  - Buffer—toll revenue protection and violation reduction, real estate available, cost.
  - Shoulder and lanes—mandatory design standards dictated by state DOT.
  - Safety, managed lane operation policies, allowable vehicles, design vehicle operational characteristics, key operational goals and objectives, implications from financial operational plan, enforcement plan, maintenance plan, incident management, corridor-specific conditions, ingress/egress operations, driver expectancy and human factors.
  - Speed, stopping sight distance, volumes, accident history/patterns, percent of buses or trucks in either the managed lane or right shoulder of the freeway.
- Toll systems, locations, and enforcement factors:
  - Safety, ingress/egress locations as indicated by toll/revenue study.
  - HOV detection—reliability of current technology.
  - Travel sheds, goals of project (revenue verses traffic management), short- and long-term changes in traffic, cost.
  - Safety and maintaining minimum operating speeds on lanes exclusively using electronic toll collection (ETC) of paramount importance.
  - Type of tolling allowed—automated vehicle identification (AVI) and/or pay-by-mail.

MANAGED LANE PRACTITIONER FOCUS GROUP 1

Introduction

On March 13, 2015, an online focus group of managed lane practitioners was conducted to review established practice for managed lane design trade-offs and evaluate the performance with different design environments (Study 5R.2). The purpose of the online focus group was to seek practitioner perspectives on which factors and measures of effectiveness are to be prioritized for adjusting the cross-section by the three design elements under consideration—lane, shoulder, and buffer width.

Methodology—First Session

A total of two focus groups were conducted (the first is discussed here, and the second is discussed later in this chapter). A third focus group was replaced with the online survey of practice described previously in this chapter because it was a more efficient and comprehensive option for compiling the requisite data. Each session was held online in a webinar format. Participants opened a browser to view presentation material, and they called into a toll-free number to listen and speak. No line was muted during the webinar; all participants were free to discuss at any point. Additionally, participants had the option to either identify themselves by linking their telephone line to their browser session or remain unidentified when speaking by using an unlinked telephone line. Most participants were unlinked in the course of the webinar session. Each session was managed by a single project team moderator assisted by topical presenters.

The first session was conducted on March 13, 2015. A total of 17 individuals participated in the focus group, representing 10 different agencies—six state departments of transportation, two regional congestion management agencies, and two metropolitan planning organizations. The agenda for the first focus group session comprised the following:

- Introduction of focus group procedures and protocols.
- Overview of webinar presentation and discussion format.
- Presentation of the NCHRP 15-49 study overview.
- Presentation of the summary of current practice in design trade-offs, as summarized in the previous section of this document.
- Presentation of the survey findings in design trade-offs, as summarized in the previous section of this document.
- Discussion on agency preferences for design trade-offs.

Focus Group 1 Discussion Topics

In the first focus group session, the research team facilitator seeded discussion with the following two questions:

1. Succinctly describe the process your agency uses to decide what should be the widths of lanes, shoulders, and buffers
    - What factors—not otherwise described in the summary of existing practice and survey of practitioners—are influential in the decision process?
    - What factors were preserved as highest priority in the decision process?
    - When in the course of project development, are different analyses performed?
    - What technical studies are required for environmental clearance?
    - Are there any differences in procedures for managed lane projects that primarily comprise a conversion of existing infrastructure as compared to new or reconstruction?
    - Does a decision to reconstruct affect the prioritization of lane, shoulder, and buffer widths?

2. Have you observed any differences in operating speed or lateral position of vehicles using facilities of different widths?
    - What impacts have there been to operations, enforcement, signage, or toll collection due to width decisions?
    - Have there been any observed changes in crash rates related to width decisions?

Focus Group 1 Findings

Practitioners provided the following principal points of commentary regarding the literature review and in response to the questions posed by the facilitator:

- **Factors not mentioned in the current guidance**. Practitioners highlighted the different design environments for highly constrained conditions. If reconstruction in these areas is conducted, it provides an opportunity to revise previous design decisions. Additionally, the typical cross-section will be different from that at entrance/exit ramps, whereby the provision of outside shoulders may be compromised further. Some practitioners also advised that guidance should identify undesirable widths—for example, no buffer width between 5 and 8 ft in order to discourage vehicles from inappropriately using the buffer for refuge purposes.
- **Preservation desires**. All practitioners act to preserve the outside shoulder first. However, some practitioners aim to preserve the inside shoulder, whereas others aim to preserve the buffer space, especially when tubular markers are desired for separation purposes. One practitioner indicated that access philosophy (e.g., limited vs. continuous access) is equally considered with cross-section reductions in order to accommodate constrained environments.
- **Special design considerations**. Practitioners indicated that the guidance, from one agency to another, is consistent in terms of process for reducing inside shoulders. However, certain concerns such as drainage and snow storage requirements are not addressed in the generalized trade-offs. In fact, as one practitioner stated, drainage spreading does not work with a 2-ft shoulder because the requirement is to drain out, not toward, the barrier. As such, understanding the effects of trade-offs in the left-side shoulder on these issues and issuance of special design procedures to mitigate these concerns would be helpful.
- **Crash rates with different widths**. Practitioners were particularly interested in different crash rates related to reduced widths of buffers and shoulders. One practitioner stated his/her state research institution looked at specific crash rate changes within different design environments on two managed lane corridors and noted that there was no increase in crash rates observed with reduced shoulders. However, another practitioner noted his/her state has observed increased crashes with a reduction in inside shoulder width. This practitioner advised the research team to focus more on severe fatality and injury crashes, though, in order to design access around minimizing these issues.

LITERATURE REVIEW—LATERAL POSITION

Previous studies on lateral position of vehicles within a driving lane were mostly investigated for two-lane rural roads and curves. When looking at how the application of rumble strips affects the lateral position of vehicles within the lane, researchers have used piezoelectric

sensors in a Z-configuration (*8*). The same configuration using road tubes was deployed when investigating lateral position and speed at horizontal curves (*9, 10*). Fitzsimmons et al. analyzed the speed and lateral position data for 23,468 vehicles traveling on two horizontal curves in central Iowa. The tubes were placed in five equally spaced stations along the curve, and the spacing was determined by the distance of the passenger car (PC) and pickup truck (PT) points. The study used a linear mixed-effects model to attempt to predict speed and lateral position along curves. The researchers found that vehicle type, time of day, and travel direction were significant factors affecting a vehicle's speed and lateral position. Researchers looked at driver behavior and found that speed entering the curve has a direct impact on lateral position and acceleration near the center of the curve (*9*).

Hallmark et al. (*10*) performed an odds ratio analysis to correlate speed and lateral position on curves. The study found that the odds of a near-lane crossing were 2.37 to 4.47 greater at higher speeds. These results were statistically significant and imply that the higher the speed, the greater the odds of a near-lane crossing. Odds of a near-lane crossing for vehicles traveling more than 5 mph when compared to slower vehicles were not statistically significant. Gates et al. (*11*) used video footage to gain insight on the impact of centerline and shoulder rumble strips on driver behavior. High-definition cameras were mounted on poles (7 to 20 ft high) to record traffic during daylight hours. Lateral position was measured according to the center of the lane and the center of the vehicle with the license plate being the reference point. The vehicle was considered centered if it was within 6 inches to the left or right of the center of the lane. The study found that rumble strips had a significant impact on lateral position on curve and tangent segments. Variations existed between vehicle types, but overall vehicles tended to travel down the center of the lane when both center and shoulder rumble strips were present.

Australian researchers (*12*) used video footage to look at lateral position of cars and heavy vehicles on two-lane highways in Queensland. What was of interest was the interaction of passenger cars with freight vehicles towing two or more trailers. Lateral position was used as a measure to assess driver behavior. For data collection, a camera was on an overpass overlooking the road. Lateral position was defined as the distance between the middle of the road and the nearest edge of the vehicle. Lateral position was measured off the video image by using a scaled overlay on the computer screen. The scale divided each lane into eight divisions. Four hours of video was recorded, and a total of 3,151 vehicles were observed. The study showed that typically, passenger cars do not change their lateral position when heavy trucks travel in the opposite direction. Researchers also found that heavy trucks tend to occupy part of the shoulder, while passenger cars tend to straddle the edgeline.

In summary, the literature review identified two methods of gathering data for lateral position: use of on-pavement sensors or road tubes, and use of video cameras overlooking a roadway segment. Lateral position research has been a concern mainly on curves and tangent segments of two-lane rural highways. Researchers have used lateral placement as a measure to determine driver behavior and have not sought to identify a relationship with crash rates.

TYPICAL LATERAL POSITIONS—AERIAL PHOTOGRAPHS

To have an appreciation of typical lateral positions on a freeway, the research team used aerial photographs to determine the lateral position of vehicles in general-purpose lanes. Segments within three states (California, Minnesota, and Texas) were selected from the list of sites considered in other parts of this research project. Using the ruler function, the following information was collected:

- Lane width.
- Car width.
- Space between the middle of the markings on the left side of the lane and left edge of the car.
- Space between the middle of the markings on the right side of the lane and right edge of the car.
- Lane where the vehicle was traveling.
- Whether there was a vehicle on the left or on the right of the subject vehicle.

A minimum of two segments per state was used in the evaluation, and data for about 100 passenger cars were collected on the general-purpose lanes. Data were collected when the vehicle was clearly visible and not obviously changing lanes. Table 15 shows the typical lateral position for passenger cars on freeways. In general, typical lateral position is about 2.3 to 2.8 ft from the lane line. The raw data indicate that there could be a small influence on lateral position when the lane width is less than 12 ft and there is a neighboring vehicle.

Table 15. Passenger car typical freeway lateral position.

Neighbor	Measurement Taken…	…to Left of 11–12 ft Lanes	…to Right of 11–12 ft Lanes	…to Left of 12–13 ft Lanes	…to Right of 12–13 ft Lanes
Vehicle in neighboring lane	Number of passenger cars with neighboring vehicle (either to left or right)	68	67	36	52
	Average ± standard deviation of lateral position (ft)	2.5 ± 0.9	2.7 ± 0.9	2.5 ± 0.9	2.9 ± 1.1
No vehicle in neighboring lane	Number of passenger cars with no neighboring car	348	349	211	195
	Average ± standard deviation of lateral position (ft)	2.2 ± 0.8	2.3 ± 0.9	2.4 ± 0.9	2.8 ± 0.9
Either condition	Number of passenger cars	416	416	247	247
	Average ± standard deviation of lateral position (ft)	2.3 ± 0.8	2.4 ± 0.9	2.4 ± 0.9	2.8 ± 0.9

DRIVING AND FIXED VIDEO DATA COLLECTION

Site Selection

The field sites selected for the lateral position study represented four states (California, Minnesota, Texas, and Washington). Only sites with one managed lane per direction were considered. To capture the influence of buffer width and type, a range of styles and widths were desired. The following buffer types (and widths shown in parentheses) were represented in the study:

- Double white (1–4.5 ft).
- Double white and single white with four yellow lines (4.9 ft).
- Double white with pylons (4–5 ft), where the pylons are 3-ft high and spaced 14 ft or 4-ft high and spaced 10 ft.
- Single white line and four yellow lines (4.1–4.9 ft).
- Single white line and single yellow line (1.7–2.2 ft).
- Single white line and two yellow lines (1.7–2.4 ft).
- Single yellow line (<1 ft).
- Single white line (1 ft).

For the sites with a fixed camera location, traffic management centers in California, Minnesota, and Washington provided the research team with video. Because of a different project to collect traffic data on managed lanes for Houston, Texas, freeways, members of the research team were able to install video cameras along the concrete barrier separating the direction of travel (see Figure 10).

Source: TTI

Figure 10. Example of fixed video installation at a Houston, Texas, site.

For driving data, freeways in and near the city of Dallas were chosen because of the use of pylons serving as a barrier between the managed lane and the general-purpose lanes. In California, freeways were chosen to provide a range of buffer widths. The routes and data collection times for the driving data were selected to increase the number of potential data points while being on segments of interest.

The geometric characteristics obtained for each site included physical components of the managed lane, adjacent general-purpose lanes, and other traits within the corridor. Data on geometric features were gathered through discussion with local agencies responsible for operating the managed lane, measurements from aerial photographs, or measurements taken when installing the fixed video cameras. Specifically, the following geometric features were collected for use in the study:

- Left shoulder width.
- Managed lane width.
- Lane separation type between ML and general-purpose lanes (e.g., painted buffer, pylons).
- Buffer width.
- Number of general-purpose lanes.
- Average lane width for the general-purpose lanes.
- Right shoulder width.

Table 16 provides the dimensions for the driving sites, while the fixed video camera sites are listed in Table 17 for the limited-access sites and Table 18 for the continuous-access sites. The video provided by Washington zoomed on curved segments, enabling the research team to gather lateral position data from curved and tangent segments. Table 17 and Table 18 specify whether the data were taken from a curved or tangent segment of the highway.

Table 16. Driving sites.

Site	ML-Len (mi)	ML-Ln_W (ft)	ML-L_Shld_W (ft)	Buf_W (ft)	Buf_Typ	GP-Num Ln	GP-Avg_Ln_W (ft)	GP-R_Shld_W (ft)
CA I-10	16.1	11.3	12.8	4.9	DW, SWTY	4	12	10
CA I-105	16.4	11.0	9.4	4.9	SWFY	3	12	11
CA I-210	19.2	11.1	2.7	1.9	SWTY	4	11	10
CA I-405	16.9	10.4	2.7	1.7	SWTY	4	11	12
CA I-605	16.2	10.4	2.2	2.2	SWSY	4	11	9
CA SR 118	10.6	11.7	2.2	2.45	SWTY	3	12	10
CA SR 134	13.2	10.9	1.8	1.7	SWSY	4	11	10
CA SR 210	18.9	11.8	14.9	4.1	SWFY	4	11.5	10
CA SR 60	11.8	10.5	1.4	1.7	SWTY	4	11	7
TX I-635	8.7	10.5	2.0	5.0	DWP	4	11	10
TX US-75	12.9	11.0	2.0	4.0	DWP	4	11	10

Note: Column headings:

- Site = name of site consisting of state and highway number.
- ML-Len = length of the freeway driven for this project (mi).
- ML-Ln_W = managed lane width (ft).
- ML-L_Shld_W = left shoulder width (ft).
- Buf_W = buffer width (ft).
- Buf_Typ = buffer type with the following codes:
  - DW, SWTY = double white and single white with four yellow lines.
  - SWFY = single white line and four yellow lines.
  - SWTY = single white line and two yellow lines.
  - SWSY = single white line and single yellow line.
  - DWP = double white lines with 36- to 39-inch-high pylons spaced 12 to 14 ft apart.
- GP_NumLn = number of general-purpose lanes.
- GP-Avg_Ln_W = average lane width of general-purpose lanes (ft).
- GP-R_Shld_W = right shoulder width of general-purpose lanes (ft).

Table 17. Fixed video camera sites—limited-access sites.

Site	Hwy	ML-Dir	Tan or Cur	ML-Ln_W	ML-L_Shld_W	Buf_W	Buf_Typ	GP-NumLn	GP-Avg_Ln_W	GP-R_Shld_W
CA 01	SR 237	EB	Tan	11.0	4.00	2.00	DW	3+2	12	18
MN 6091	I-35W	NB	Tan	11.0	4.00	2.00	DW	2	12	10
MN 6131	I-35W	SB	Tan	11.0	4.00	2.00	DW	2	12	12
MN 6231[a]	I-35W	NB	Tan	13.0	2.00	1.00	SY	4	12	3
MN 909	I-394	EB	Tan	12.0	9.00	2.00	DW	2	12	9
MN C614	I-35W	SB	Tan	11.0	4.00	2.00	DW	3	12	11
MN C907	I-394	EB	Tan	12.0	8.00	2.00	DW	2	12	10
MN C908	I-394	EB	Tan	12.0	8.00	2.00	DW	3	12	9
TX 01	US 59	NB	Tan	11.5	9.80	1.00	DW	4	11	10
TX 02	US 59	SB	Tan	11.2	9.90	1.00	DW	4	11	10
TX 03	I-10	WB	Tan	13.1	18.35	5.00	DWP	4	11.5	11
TX 04	I-10	EB	Tan	13.4	15.25	5.00	DWP	5	11.5	11
TX 05	US 59	NB	Tan	11.3	13.25	4.67	DW	4	11	12
TX 06	US 59	SB	Tan	11.5	13.40	4.50	DW	4	11	12
TX 07	US 290	EB	Tan	10.5	1.67	0.83	DW	3	11	9
TX 08	US 290	WB	Tan	10.5	1.67	0.83	DW	3	11	9
TX 09	US 290	EB	Tan	10.5	1.67	0.83	DW	3	11	9
TX 10	US 290	WB	Tan	10.5	1.67	0.83	DW	3	11	9

Note: Column headings:

- Site = name of site.
- Hwy = highway number.
- ML-Dir = direction of travel for the managed lane.
- Tan or Cur = tangent (Tan) segment or curve (Cur) segment of highway.
- ML-Ln_W = managed lane width (ft).
- ML-L_Shld_W = left shoulder width (ft).
- Buf_W = buffer width (ft).
- Buf_Typ = buffer type with the following codes:
  - SY = single yellow line.
  - DW = double white lines.
  - DWP = double white lines with 4-ft-high pylons spaced 10 ft apart.
- GP_NumLn = number of general-purpose lanes.
- GP-Avg_Ln_W = average lane width of general-purpose lanes (ft).
- GP-R_Shld_W = right shoulder width of general-purpose lanes (ft).

[a] Facility operates as a shoulder during off-peak periods.

Table 18. Fixed video camera sites—continuous-access sites.

Site	Hwy	ML-Dir	Tan or Cur	ML-Ln_W	ML-L_Shld_W	Buf_W	Buf_Typ	GP-NumLn	GP-Avg_Ln_W	GP-R_Shld_W
WA-01	SR 167	NB	Tan	11.0	9.50	1.00	SW	2	11	11
WA-02	SR 167	SB	Tan	11.3	7.77	1.00	SW	2	11	11
WA-03	SR 167	NB	Tan	10.2	8.50	2.00	DW	2	11	10
WA-04	SR 167	SB	Tan	12.8	6.47	1.00	SW	2	11	13
WA-05	SR 167	NB	Tan	12.2	8.35	1.00	SW	2	11	9
WA-06	SR 167	SB	Tan	12.2	11.00	1.00	SW	2	11	10
WA-07	SR 167	NB	Cur	12.2	8.35	1.00	SW	2	11	9
WA-08	SR 167	SB	Cur	12.2	11.00	1.00	SW	2	11	10
WA-09	SR 167	NB	Cur	11.0	9.50	1.00	SW	2	11	11
WA-10	SR 167	SB	Cur	11.3	7.77	1.00	SW	2	11	11

Note: Column headings:

- Site = name of site.
- Hwy = highway number.
- ML-Dir = direction of travel for the managed lane.
- Tan or Cur = tangent (Tan) segment or curve (Cur) segment of highway.
- ML-Ln_W = managed lane width (ft).
- ML-L_Shld_W = left shoulder width (ft).
- Buf_W = buffer width (ft).
- Buf_Typ = buffer type with the following codes:
  - SY = single yellow line.
  - DW = double white lines.
  - DWP = double white lines with 4-ft-high pylons spaced 10 ft apart.
- GP_NumLn = number of general-purpose lanes.
- GP-Avg_Ln_W = average lane width of general-purpose lanes (ft).
- GP-R_Shld_W = right shoulder width of general-purpose lanes (ft).

Fixed Video Camera

Video data using a fixed video camera were obtained from San Jose, California; Houston, Texas; within the Minneapolis/St. Paul, Minnesota region; and within the Orillia/Kent, Washington region. These data were retrieved from either contacting the operating agencies directly or having a research team place stationary cameras in the field. Data from the San Jose, Minnesota, and Washington sites were obtained by contacting the Santa Clara Valley Transportation Authority, the Minnesota Department of Transportation, and the Washington State Department of Transportation, respectively. Individuals from all agencies provided the research team with video samples representing either a period or an entire day of operation. Data from the Houston, Texas, location were obtained from stationary cameras installed by an in-field research team.

The focal point for each camera was centered on the managed lane, with the background capturing traffic conditions from the adjacent general-purpose lanes. Cameras captured either a period of observed traffic (e.g., morning, afternoon), or an entire day or two of operation depending on what the agency could provide.

Driving

An instrumented vehicle was used to obtain in-field data for a selection of sites. For this protocol, an instrumented vehicle followed a vehicle traveling in the managed lane. The schematic in Figure 11 shows a simplified example of how the data collection in the instrumented vehicle (shown in red) was accomplished using light deflection and ranging (LIDAR) to obtain speed and following distance and video to observe lateral position.

Source (base image): Google Earth™ Mapping Service

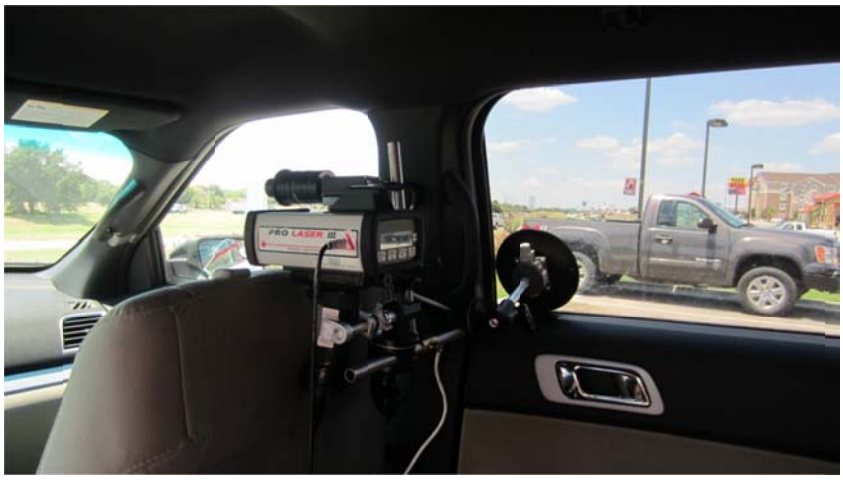
Figure 11. Schematic of driving data collection in instrumented vehicle.

The instrumented vehicle was outfitted with a still-frame video camera, a LIDAR detector, and a global positioning system (GPS) data logger. The still-frame video camera captured single black-and-white images, recording the images once per second. The LIDAR detector measured the distance from the instrumented vehicle to the followed vehicle. The GPS data logger recorded the geographical coordinates (latitude, longitude) and speed of the instrumented vehicle.

Most of the instrumentation was placed on or near the front passenger seat to maximize the probability of obtaining good video and speed data. The still-frame video camera and LIDAR detector were mounted on a metallic pole, which was affixed right below the head rest for the passenger seat. The placement allowed the camera to have an unobstructed view through the front windshield. The windshield was also clear and not tinted. Figure 12 shows the placement of the video camera and LIDAR detector in the vehicle. The GPS data logger was placed on top and in the middle of the front dashboard to increase the probability of obtaining a strong satellite signal for the GPS.

Data from each instrument were transmitted into an onboard laptop computer. From the GPS data logger, the computer had a log of coordinates and a date and time stamp for each second of a trip. A separate data stream archived the distance between the lead and instrumented vehicles for each second of travel measured from the LIDAR detector. Also, the video camera

had a time stamp that marked each frame with the recorded time. The post-processing methodology used the date and time elements from all three instruments as the unique identifier to match data.



Source: TTI

Figure 12. Placement of the camera and LIDAR detector in the instrumented vehicle.

DRIVING AND FIXED VIDEO DATA REDUCTION

Fixed Video Camera

The following data were collected for vehicles recorded by the fixed video cameras:

- Time of day.
- Time in the video.
- Type of vehicle.
- Whether there was a vehicle in the lane next to the managed lane vehicle. Figure 13 is an example of when a vehicle was in the proximity of the managed lane vehicle.
- Whether the general-purpose lane was traveling 10 mph slower than the ML, in the opinion of the technician.
- Lateral position of the vehicle within the lane.

Data were collected during daylight and dry pavement conditions. The next sections give clarification on some of the data fields collected.

Type of Vehicle

Vehicle classes used when reducing the video data included:

- Passenger car: all four-wheeled cars and station wagons.
- Pickup truck: all sizes of pickup trucks.
- SUV/van: all sizes of SUVs and passenger vans.
- Bus: all buses and heavy vehicles.
- Emergency vehicle: police vehicles and ambulances, but not maintenance vehicles.
- Motorcycle: all two-wheeled or three-wheeled vehicles (including mopeds).

Source: TTI

Figure 13. Vehicle in general-purpose lane next to vehicle in managed lane.

Lateral Position of Vehicle Within the Managed Lane

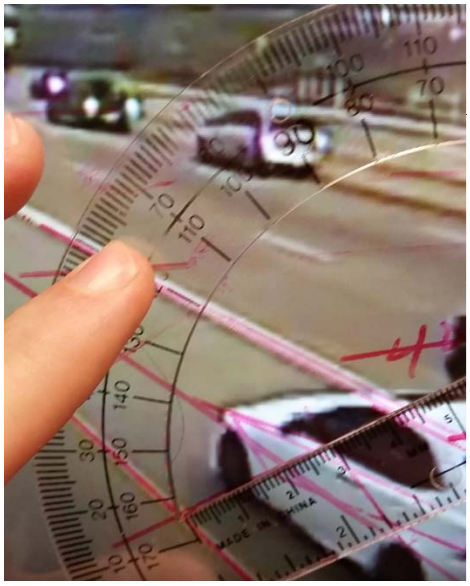
Lateral position data were reduced from the video on desktop computers in the office. To determine lateral position, a transparency sheet was placed over the computer monitor. The pavement marking lines and a perpendicular line across the lane were drawn on the transparency. Road features (such as diamond markings) or vehicle features (i.e., rear bumper) were used to draw a horizontal line across the lane in order to ensure that the horizontal line was perpendicular to the pavement markings and straight according the plane of the video. Figure 14 shows an example of using road features to draw a straight line across the managed lane.

Figure 14 shows the view from a camera placed on the concrete barrier. In the picture, the left shoulder pavement marking is outlined and the inside pavement marking of the buffer is outlined. The perpendicular line to these markings was used as the stopping point where the lateral position measurement was taken. Once the front tire of a vehicle in the managed lane crossed the line drawn between points 1 and 2, the video was paused and the distance between the edgeline marking and the wheel was measured using a ruler, as shown in Figure 15.

The ruler was aligned to the horizontal line, the tick mark “0” was placed along the inside edge of the pavement marking, and then the tick marks from the left pavement marking to the wheel were noted. After the lateral position in millimeters was read, the lane width was measured with the ruler. For some videos, it was better to measure the right wheel instead of the left wheel. Lane width measurements were taken in the field or using aerial photographs for each site where video footage was recorded. These measurements allowed the research team to scale the lateral position readings from millimeters to feet for each vehicle observed.

Source: TTI

Figure 14. Pavement marking coordinates.



Source: TTI

Figure 15. Lateral positioning measurement.

Driving Video

Video was obtained from an instrumented vehicle that drove multiple times on a corridor with managed lanes. The instrumented vehicle recorded activity of the moving vehicle located directly in front of the instrumented vehicle. The instrumented vehicle was equipped with a camera that recorded and archived a still-frame image every second, a LIDAR detector that measured distance to the followed vehicle, and a GPS data logger recording position and speed data. Each photograph was automatically saved with a time stamp depicting the date and time of day the picture was captured. All LIDAR readings and GPS coordinates were

entered into a spreadsheet and matched according to the time stamp of when the data point was recorded. A researcher would enter on the spreadsheet the following information from the picture:

- Left shoulder treatment.
- Buffer treatment.
- Whether the left pavement marking was visible.
- Whether the picture was clear enough to obtain coordinates.
- Whether the vehicle was on a tangent (T), a curve to the left (LC), a curve to the right (RC), or within an access opening or entrance/exit point. Vehicles within an access opening or at entrance/exit points were not reduced.
- Whether the vehicle's speed was affected, in the opinion of the technician.
- Pixel coordinate for the left pavement marking.
- Pixel coordinate for the edge of the right rear wheel of the car.
- Pixel coordinate for the right pavement marking.
- Speed of instrumented vehicle.

Only pictures with a clear resolution and where all road features were visible were used in data reduction. The picture file was opened with Microsoft Paint to obtain the pixel coordinates of the right wheel. Figure 16 shows the process of obtaining the pixel coordinates.

Figure 16(a) shows the inside edge of the left pavement marking. The coordinate is taken at approximately the edge of the yellow line. Figure 16(b) shows the edge of the rear right wheel of the vehicle. The point taken for the right wheel was outside at the edge of the right wheel. Figure 16(c) shows the edge of the right pavement marking. Only horizontal coordinates were noted. The coordinate was taken at the inside edge of the pavement marking. Once all pixel coordinates were entered, the difference between pixel coordinates was calculated between pavement markings and between the right wheel and right pavement marking. The LIDAR distance was used to determine the reference scale from millimeters on the screen to estimated feet within the managed lane by using Equation 1.

$$WV = LD * 304.8 \tag{1}$$

Where:

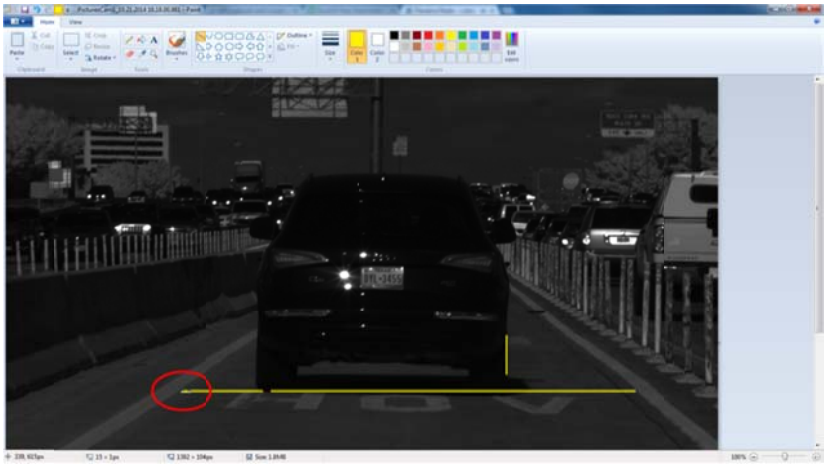
WV = reference view (mm).
LD = distance between instrumented vehicle and vehicle being followed (ft).

After the window view and difference in pixels were calculated, Equation 2 was used to calculate the lateral position in millimeters.

$$LP = DP * (0.000084434 * WV - 0.0065201) \tag{2}$$

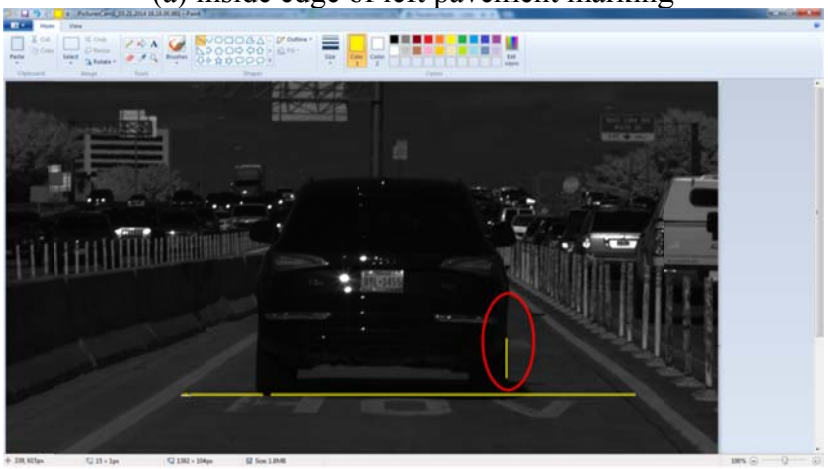
Where:

LP = lateral position (mm).
WV = window view (mm).
DP = distance between instrumented vehicle and vehicle being followed (ft).



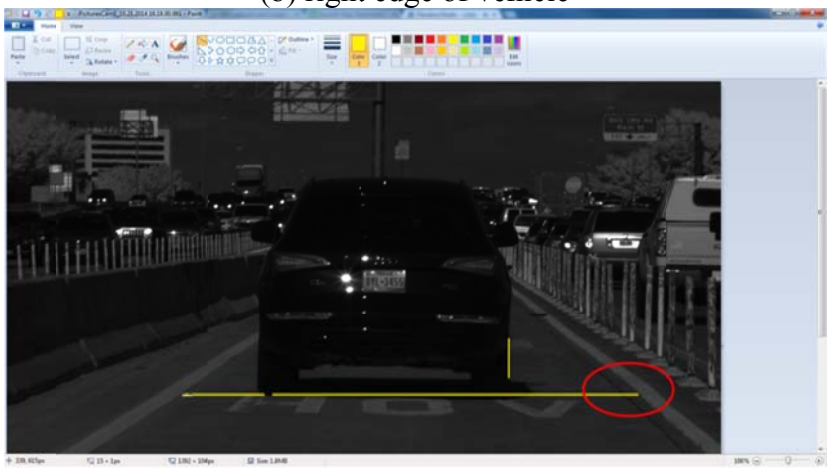
Source: TTI

(a) inside edge of left pavement marking



Source: TTI

(b) right edge of vehicle



Source: TTI

(c) inside edge of right pavement marking

Figure 16. Example of data reduction steps for diving video.

Using the LIDAR distance and speed reading from the GPS on the instrumented vehicle, a formula was developed to estimate the speed of the vehicle being followed. The formula developed to predict speed is shown in Equation 3:

$$S_f=(D_{n+1}-Dn)/\Delta t \quad (3)$$

Where:

S_f = the speed of the vehicle being followed.
D_{n+1} = the distance reading at n+1 time.
Dn = the initial distance.
Δt = the time interval.

To ensure data quality, limits for non-realistic outliers were set for lane width and calculated speed. If the calculated speed reading was negative or over 90 mph, then the associated data were not used. Data were also not used for occurrence when lane readings were below 9 ft or above 13 ft. Both occurrences could be due to an error in LIDAR reading, or due to difficulties in aiming the LIDAR gun. All valid data points were compiled into a main database for analysis.

Obtaining the lane width value from the pixel image resulted in a variance of 2 to 4 ft in lane width for one highway segment. A geometric table was created as the database for all sites to calibrate lane width values and lateral position values. The geometric table had values for lane width, shoulder width, and buffer width measured using aerial photographs. Equation 4 provided an additional step that calibrated lateral position readings:

$$LP\_ADJ=LP*(LW\_ADJ/LW\_IMG) \quad (4)$$

Where:

LP_ADJ = the adjusted lateral position expressed in feet.
LP = the lateral position reading from the image expressed in feet.
LW_ADJ = lane width measurement from aerial photographs in feet.
LW_IMG = lane width measured from the image expressed in feet.

This calibration, and other tests of the procedure, further ensured that lateral position readings were accurate within 6 inches.

Additional Data Reduction for Fixed Video Camera and Driving Data

When reducing the dataset, some data points represented the left lateral position and some represented the right lateral position depending on which side of the vehicle provided the better view. Because most of the dataset was left lateral position, the right lateral positions were converted to be left lateral positions through the use of the following assumed vehicle wheel base widths:

- Passenger car = 6.0 ft, based on *Green Book* Figure 2-1 (*7*).
- SUV/van = 6.0 ft, based on *Green Book* Figure 2-2 (*7*).

- Pickup truck = 6.5 ft, estimated from http://dodgeram.info/2001/dimensions.html and https://www.fleet.ford.com/truckbbas/topics/2012/12_SD_Pickups_SB.pdf.
- Transit or school bus = 8.5 ft, based on *Green Book* Figure 2-4 (*7*).
- Emergency vehicle = 8.0 ft, based on the following website: http://www.hortonambulance.com/type1.cfm.
- Motorcycle = 2.3 ft, estimated from https://www.fleet.ford.com/truckbbas/topics/2012/12_SD_Pickups_SB.pdf.

The resulting dataset included over 7000 vehicles. The range of cross-section dimensions included in the dataset is shown in Table 19.

Table 19. Range of shoulder, lane, and buffer widths represented in lateral position dataset.

Value	Shoulder Width (ft)	Lane Width (ft)	Buffer Width (ft)
Minimum	1.4	10.4	0.8
Maximum	18.4	13.4	5.0
Range	16.9	3.0	4.2

DRIVING AND FIXED VIDEO FINDINGS

Preliminary Findings

The average and standard deviation for lateral position (left) is shown in Table 20 for the driving sites and in Table 21 for the fixed video camera sites. These tables also provide the total number of lateral position readings available for the analysis. Overall, the vehicles in the managed lane are about 2.5 ft from the left edgeline. Figure 17 shows an example of a passenger car near the center of the managed lane.

Table 20. Average left lateral position by site for driving sites.

Site	SW (ft)	LW (ft)	BW (ft)	Buffer	Count	Ave Lf_LP	StdDev Lf_LP
CA I-10	12.8	11.3	4.9	DW, SWTY	180	2.9	0.9
CA I-105	9.4	11.0	4.9	SWFY	205	2.9	0.8
CA I-210	2.7	11.1	1.9	SWTY	348	2.8	0.8
CA I-405	2.7	10.4	1.7	SWTY	144	2.9	0.8
CA I-605	2.2	10.4	2.2	SWSY	26	2.6	0.8
CA SR 118	2.2	11.7	2.4	SWTY	172	3.3	1.1
CA SR 134	1.8	10.9	1.7	SWSY	142	3.0	0.8
CA SR 210	14.9	11.8	4.1	SWFY	83	2.6	0.8
CA SR 60	1.4	10.5	1.7	SWTY	8	2.9	0.6
CA SR 91	1.8	10.9	2.0	SWTY	13	3.3	1.2
TX I-635	2.0	10.5	5.0	DWP	865	2.4	0.8
TX US-75	2.0	11.0	4.0	DWP	1169	2.0	0.8
All Sites	NA[a]	NA	NA	NA	3355	2.5	0.9

Note: Column headings:

- Site = name of site consisting of state and highway number.
- SW = left shoulder width (ft).
- LW = managed lane width (ft).
- BW = buffer width (ft).
- Buffer = buffer type; see Table 16 for codes definitions.
- Count = number of vehicles included in dataset.
- Ave Lf_LP = average left lateral position.
- StdDev Lf_LP = standard deviation for left lateral position.

[a] NA = value not applicable or meaningful for all site totals or averages.

Source: TTI

Figure 17. Example of lateral position for vehicle near center of the managed lane.

Table 21. Average left lateral position by site for fixed view sites.

Site	Road	LA or CA	Tan or Cur	SW (ft)	LW (ft)	BW (ft)	Buffer	Count	Ave Lf_LP	StdDev Lf_LP
CA 01	SR 237	LA	Tan	4.0	11.0	2.0	DW	1097	1.9	1.0
MN 6091	I-35W	LA	Tan	4.0	10.0	3.0	DW	203	1.2	0.9
MN 6131	I-35W	LA	Tan	3.0	10.5	2.0	DW	191	1.7	0.9
MN 614	I-35W	LA	Tan	3.0	10.0	3.0	DW	109	1.7	1.2
MN 6231	I-35W	LA	Tan	2.0	12.0	0.8	SY	203	3.9	1.3
MN 908	I-394	LA	Tan	8.0	11.8	2.0	DW	152	3.0	1.0
MN 909	I-394	LA	Tan	8.5	11.5	3.0	DW	132	2.4	1.2
TX 01	US 59	LA	Tan	9.8	11.5	1.0	DW	190	1.8	1.5
TX 02	US 59	LA	Tan	9.9	11.2	1.0	DW	184	2.2	1.3
TX 03	I-10	LA	Tan	18.4	13.0	5.0	DWP	114	3.9	1.5
TX 04	I-10	LA	Tan	15.3	13.0	5.0	DWP	100	2.2	0.9
TX 05	US 59	LA	Tan	13.3	11.3	4.7	DW	187	3.1	1.2
TX 06	US 59	LA	Tan	13.4	11.5	4.5	DW	289	3.0	1.3
TX 07	US 290	LA	Tan	1.7	10.5	0.8	DW	179	2.7	0.8
TX 08	US 290	LA	Tan	1.7	10.5	0.8	DW	119	2.9	0.8
TX 09	US 290	LA	Tan	1.7	10.5	0.8	DW	142	2.8	0.8
TX 10	US 290	LA	Tan	1.7	10.5	0.8	DW	107	2.7	0.8
WA-01	SR 167	CA	Tan	9.50	11.0	1.00	SW	177	2.3	1.0
WA-02	SR 167	CA	Tan	7.77	11.3	1.00	SW	170	2.5	0.9
WA-03	SR 167	CA	Tan	8.50	10.2	2.00	DW	108	1.9	0.8
WA-04	SR 167	CA	Tan	6.47	12.8	1.00	SW	104	2.7	1.0
WA-05	SR 167	CA	Tan	8.35	12.2	1.00	SW	108	3.5	1.0
WA-06	SR 167	CA	Tan	11.00	12.2	1.00	SW	111	3.4	1.2
WA-07	SR 167	CA	Cur	8.35	12.2	1.00	SW	108	0.8	0.8
WA-08	SR 167	CA	Cur	11.00	12.2	1.00	SW	198	1.8	0.8
WA-09	SR 167	CA	Cur	9.50	11.0	1.00	SW	107	3.1	1.0
WA-10	SR 167	CA	Cur	7.77	11.3	1.00	SW	116	3.1	1.1
All Sites	NA[a]	NA	NA	NA	NA	NA	NA	5005	2.5	1.0

Note: Column headings:

- Site = name of site.
- Road = name of road for site.
- LA or CA = limited access (LA) or continuous access (CA).
- Tan or Cur = tangent (T) segment or curve (C) segment of highway.
- SW = left shoulder width (ft).
- LW = managed lane width (ft).
- BW = buffer width (ft).
- Buffer = buffer type; see Table 17 for codes definitions.
- Count = number of vehicles included in dataset.
- Ave Lf_LP = average left lateral position.
- StdDev Lf_LP = standard deviation for left lateral position.

[a] NA = value not applicable or meaningful for all site totals or averages.

Statistical Evaluations

Variable Selection

During preliminary evaluations, the reviews identified characteristics of the dataset that needed to be considered during the evaluation. As expected, narrow lane widths were typically associated with narrow shoulder and buffer widths. If that relationship were always true, then the shoulder, lane, and buffer widths would be correlated, and not all variables would be able to be in the model. By combining the driving and fixed video camera datasets, sufficient variability in shoulder, lane, and buffer widths existed so that all three variables could be included.

In addition to the site characteristics and level of access, conditions present when the lateral position reading was taken could affect a driver's decision. The type of vehicle, especially motorcycles, had an obvious influence on lateral position. Other conditions measured included whether a vehicle in the neighboring general-purpose lane was near the managed lane vehicle and whether the technician believed the managed lane vehicle's speed could be 10 mph higher than the general-purpose lanes. While a neighboring general-purpose vehicle could be next to the managed lane vehicle without having the 10-mph speed difference, for this dataset, these variables were highly correlated. Therefore, only one of the two variables (vehicle in neighboring lane or managed lane vehicle more than 10 mph higher) could be retained in the model. The team selected the variable for whether a neighboring general-purpose vehicle was present because stronger statistical models resulted.

Initial models did not produce very satisfactory results, so the sites and data were reviewed to identify other variables or other relationships that could help to explain the variations observed. Two changes were identified. The variable pylon (yes or no) was added because it appears that left lateral position is smaller for those sites with pylons. The other change was to model the shoulder, lane, and buffer widths as parabolic curves. An advantage to using the parabolic curve function is that it reflects changes in width having minimal influence when the width is large and having much greater influence when the width is small. A parabolic curve has a portion where the curve decreases to a vertex, after which it increases. To improve the ability to easily interpret the results, the vertex of the curves was set to fall outside the available range for the variable.

Models

The best fit model is shown in Table 22. The sign of lane width and shoulder width should be interpreted in the opposite direction of the rest of the variables because of how these shifted variables were defined. The results demonstrate that in most cases, the lateral position for most of the vehicle types is significantly different from a passenger car. As anticipated, larger vehicles (e.g., buses) are closer to the left edgeline, while motorcycles are farther from the edgeline. When a general-purpose vehicle is next to the managed lane vehicle, the managed lane vehicle is 0.32 ft closer to the edgeline.

Table 22. Linear mixed-effect model.

Variable[a]	Estimate	Std. Error	DF	t-value	p-value
Reference[b]	3.14528	0.22674	8310	13.87173	0.00000
TpVeh=B	−1.23188	0.07862	8310	−15.66793	0.00000[c]
TpVeh=EM	−0.39833	0.245064	8310	−1.62546	0.1041[c]
TpVeh=MC	1.92241	0.08664	8310	22.18856	0.00000[c]
TpVeh=PT	−0.27951	0.03267	8310	−8.55412	0.00000[c]
TpVeh=V	0.092721	0.02188	8310	4.23762	0.00000[c]
Veh_GP=Yes	−0.31771	0.02037	8310	−15.59416	0.00000
Pylons=Yes	−0.92541	0.37144	34	−2.49143	0.0178
sqBW	0.03180	0.01421	34	2.23837	0.0319
sqLW.r14	−0.13387	0.02738	34	−4.88866	0.00000
sqSW.r19	.00361	0.00114	34	3.16544	0.00033
Hor=LC	−1.69920	0.20453	8310	−8.30779	0.00000
Hor=RC	0.44487	0.09033	8310	4.92481	0.00000
sqBW:Hor=LC	0.03796	0.00548	8310	6.91957	0.00000
sqBW:Hor=RC	−0.01289	0.00584	8310	−2.20807	0.0273
sqSW.r19:Hor=LC	0.00357	0.00065	8310	5.50724	0.00000

Note: Column headings:

- Estimate = natural logarithm of the ratio: odds (coefficient level)/odds (reference level). In the case of reference level, estimate is the log-odds of the average yielding rate at the reference level.
- Std. Error = standard error of value.
- DF = degree of freedom.
- t-value = conservative estimate of the z-value, which is the standard normal score for estimate, given the hypothesis that the actual odds ratio equals 1.
- p-value = probability that the observed log-odds ratio be at least as extreme as estimate, given the hypothesis that the actual odds ratio equals 1.

[a] Variables included in the statistical evaluation:

- TpVeh = type of vehicle: passenger car (PC), pickup truck (PT), SUV/van (V), transit or school bus (B), emergency vehicle (EM), motorcycle (MC).
- Veh_GP = was there a vehicle next to ML vehicle? (yes or no).
- Pylons = were pylons present? (yes or no).
- sqBW = square of buffer width.
- sqLW.r14 = square of lane width with a reference point of 14.
- sqSW.r19 = square of shoulder width with a reference point of 19.
- Hor = horizontal alignment, left curve (LC), right curve (RC), or tangent (Tan).

[b] Reference level left lateral position in the model is estimated for the following conditions:

- TPVeh = PC.
- Veh_GP = no.
- Pylons = no.

[c] These p-values require an adjustment for multiple comparisons if inferences about different lateral position values among vehicles are intended.

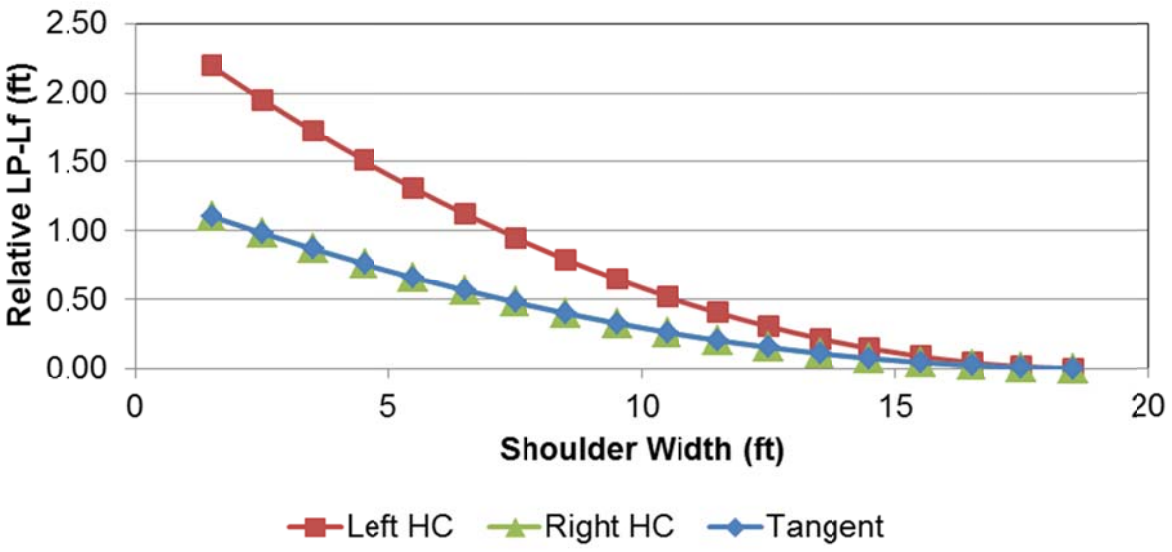
Drivers shy away from the pylons (see example in Figure 18). When pylons are present, drivers are 0.93 ft closer to the left edgeline as compared to when the pylons are not present. Horizontal alignment and the direction of the horizontal curve are influential on lateral position. Drivers are closer to the left edgeline by up to 1.7 ft when on a curve to the left, and drivers are farther from the left edgeline by up to 0.44 ft when on a curve to the right, depending on assumed shoulder, lane, and buffer widths. The model also tested if access to the managed lane (i.e., continuous vs. limited access) had an effect on lateral position. The variable was found not significant; therefore, it was not included in the final model.

Source: TTI

Figure 18. Example of lateral position for vehicle shifted away from pylons and close to the concrete barrier.

Illustration of Lateral Positions for Key Variables

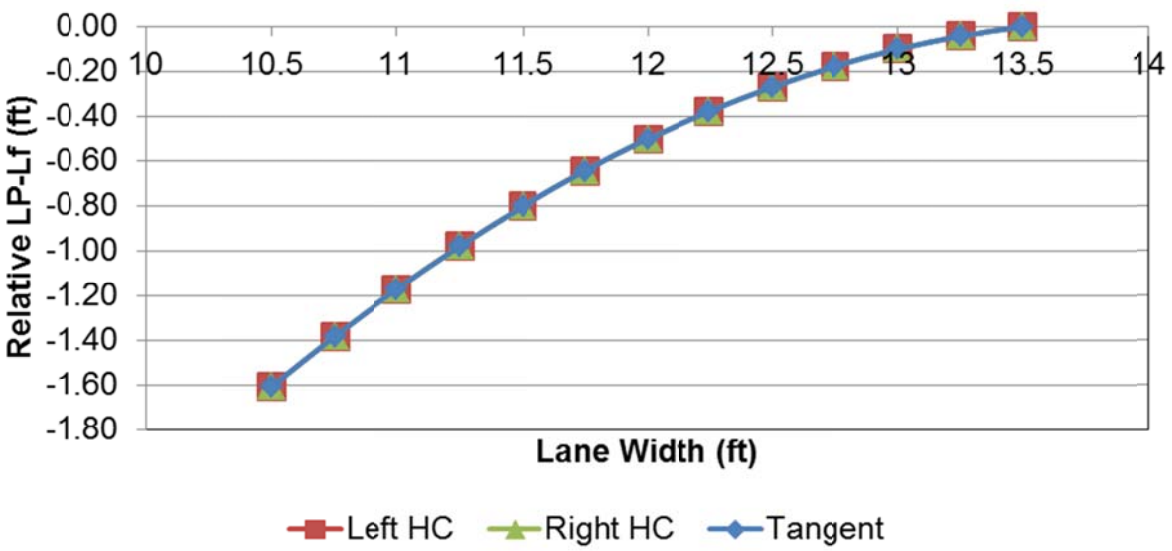
Figure 19 illustrates the relationship between lateral position and shoulder width. Note that the graph is a plot of regression findings showing results for the complete range between the minimum of 1.5 ft and the maximum of 18.5 ft. For some agencies, shoulders more than 4 ft and less than 8 ft are avoided because drivers may believe sufficient width is available for refuge. The plot shows that when the left shoulder of a tangent section or a horizontal curve to the right is at the minimum for the dataset (about 1.5 ft), drivers tend to be 1.11 ft farther to the right of the left edgeline (i.e., left lateral position increases), compared to when shoulder width is 18.5 ft. This curved function also implies that modifying a 6.5-ft shoulder to a minimum shoulder (i.e., 1.5 ft) will result in drivers moving to the right about 0.54 ft; however, if an 18.5-ft shoulder is reduced by 5 ft, the impact in operations is negligible (drivers will shift only about 0.11 ft toward the right). The effects are more pronounced for drivers on curves to the left, which limit sight distance more than tangents or curves to the right. Drivers on a section with minimal shoulders appear to be more concerned with avoiding the barrier when turning left, as demonstrated by the larger left lateral position distances.



Source: TTI

Figure 19. Lateral position relative to changes in shoulder width.

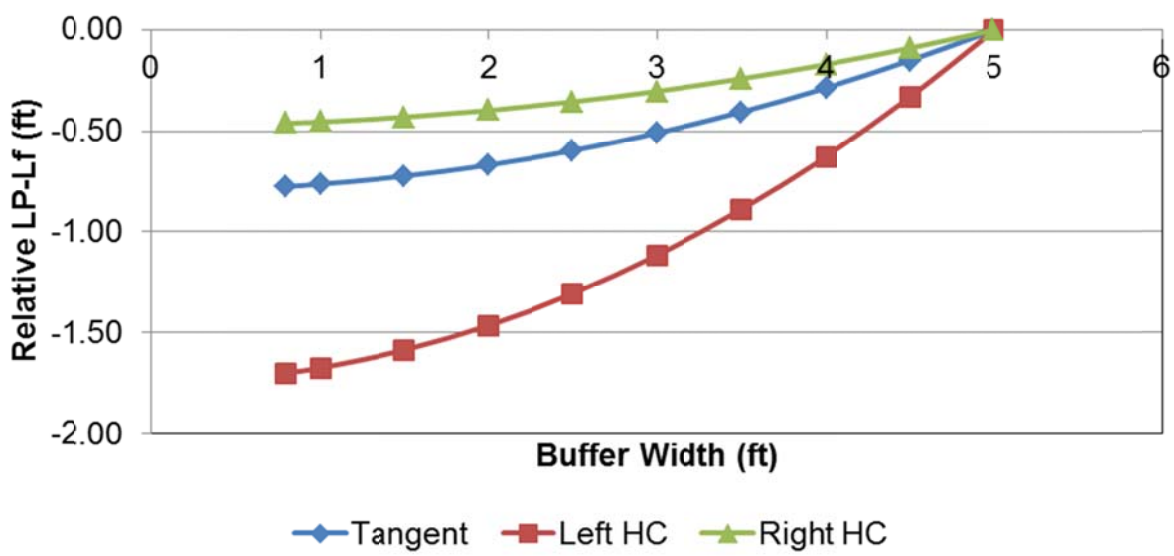
Smaller lane widths logically result in smaller left lateral positions because the measurement is a reflection of the lane width. As lane width decreases, drivers are closer to the left edgeline, as shown in Figure 20. The plot shows that when the lane width is at the minimum for the dataset (10.5 ft), drivers tend to be 1.6 ft closer to the left edgeline (i.e., left lateral position decreases), compared to when lane width is 13.5 ft. A curvilinear relationship implies different effects at different levels of lane width. When reducing a 13-ft lane by 1 ft, the model predicts a shift toward the left of about 0.41 ft. However, when reducing an 11.5-ft lane by 1 ft, the result would be drivers shifting toward the left by about 0.8 ft.



Source: TTI

Figure 20. Lateral position related to lane width.

The width of the buffer affects lateral position, with larger widths having more influence than smaller widths, as shown in Figure 21. The interaction between buffer width and horizontal alignment also affects lateral position. The presence of a horizontal curve to the left is more influential than a tangent section or a horizontal curve to the right. A difference of about 0.9 ft in lateral position exists between 5-ft and 0.8-ft buffers on tangents, whereas for left curves, there is a difference of 1.9 ft. The curvilinear relationship for tangents indicates that reducing a 2-ft buffer to a 1-ft buffer will have a negligible effect (a shift to the left of approximately 0.1 ft) compared to reducing a 5-ft buffer to 4 ft (a shift to the left of about 0.3 ft). When on a left-turning curve, drivers are 0.84 ft closer to the left shoulder with a 2-ft buffer as compared to a 4-ft buffer.



Source: TTI

Figure 21. Lateral position relative to buffer width.

Lane Position for Given Managed Lane Envelope Width

The results of the statistical evaluation can be used to develop a lateral position prediction equation, as shown in Equation 5.

$$\begin{aligned} LP\_Lf = {} & 3.14528 + 0\ (TpVeh{=}PC) - 1.23188(TpVeh{=}B) - 0.39833\ (TpVeh{=}EM) \\ & + 1.92241\ (TpVeh{=}MC) - 0.27951\ (TpVeh{=}PT) + 0.09272\ (TpVeh{=}V) \\ & - 0.31771\ (Veh\_GP{=}Yes) - 0.92541\ (Pylons{=}yes) + 0.03180\ (BW)^2 \\ & - 0.13387\ (14\text{-}LW)^2 + 0.00361\ (19\text{-}SW)^2 + 0\ (Hor{=}Tan) - 1.69920\ (Hor{=}LC) \\ & + 0.44487\ (Hor{=}RC) + 0.03796\ (BW)^2 \times (Hor{=}LC) - 0.01289\ (BW)^2 \times (Hor{=}LC) \\ & + 0.00357\ (19\text{-}SW)^2 \times (Hor{=}LC) \end{aligned} \quad (5)$$

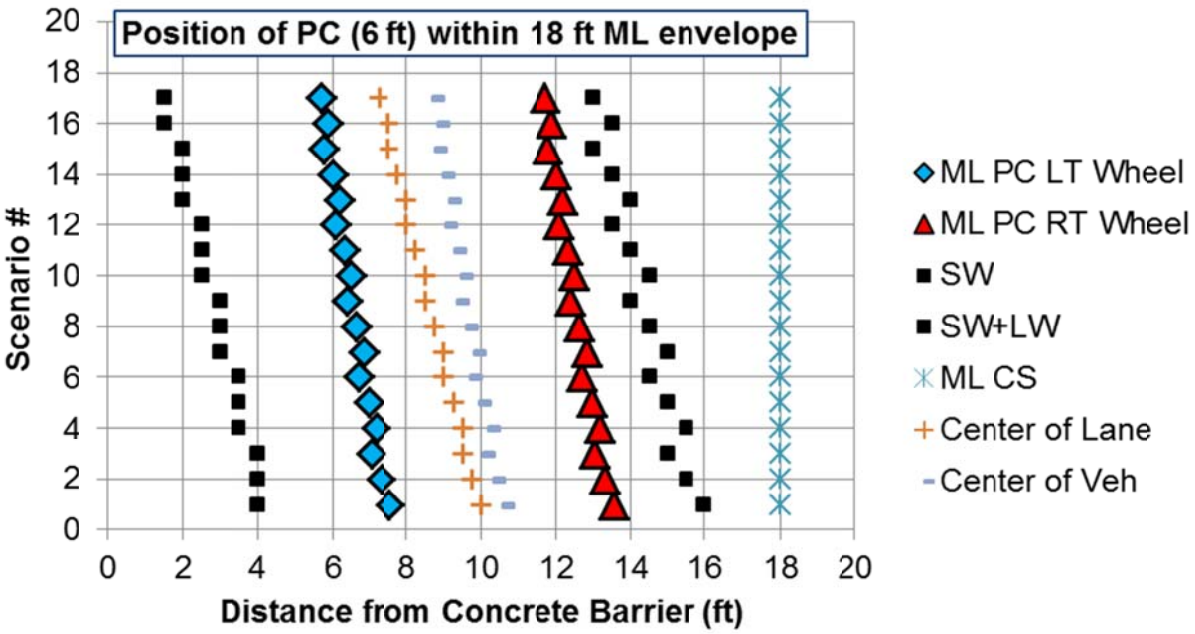
Where:

LP_Lf = left lateral position within the managed lane, in other words, the distance between the left wheel of the vehicle and the edgeline between the

		managed lane and the shoulder (ft).
TpVeh=PC	=	1 when the vehicle type is a passenger car, 0 otherwise.
TpVeh=B	=	1 when the vehicle type is a bus, 0 otherwise.
TpVeh=EM	=	1 when the vehicle type is an emergency vehicle, 0 otherwise.
TpVeh=MC	=	1 when the vehicle type is a motorcycle, 0 otherwise.
TpVeh=PT	=	1 when the vehicle type is a pickup truck, 0 otherwise.
TpVeh=V	=	1 when the vehicle type is a van, 0 otherwise.
Veh_GP=Yes	=	1 when a vehicle is present in the general-purpose lane next to the managed lane vehicle, 0 otherwise.
Pylons=yes	=	1 when pylons are present in the buffer, 0 otherwise.
BW	=	buffer width (ft).
LW	=	lane width (ft).
SW	=	shoulder width (ft).
Hor=Tan	=	1 when the horizontal alignment is a tangent, 0 otherwise.
Hor=LC	=	1 when the horizontal alignment is a curve to the left, 0 otherwise.
Hor=RC	=	1 when the horizontal alignment is a curve to the right, 0 otherwise.

Equation 5 was used to generate graphs that could illustrate the position of a vehicle within a managed lane envelope. The graphs use a blue diamond to indicate the position of a passenger car's left wheel and red triangles to show the right wheel position. Black squares are used to illustrate the limits of the managed lane along with the edge of the shoulder and buffer. The outer edge of the managed lane envelope (shown with an ML CS abbreviation), which includes the left shoulder, managed lane, and buffer, is shown with a light blue star. To aid in quickly seeing where the vehicle is within the managed lane, a plus symbol is used to mark the center of the lane, while a dash shows the center of the vehicle. When the plus and dash are close, the vehicle is tracking toward the middle of the managed lane.

Figure 22 shows a 6-ft passenger car within an 18-ft envelope for several scenarios. The y-axis shows the scenario number, which is provided to aid in discussion. For this set of scenarios, drivers prefer to drive closer to the general-purpose traffic than the concrete barrier (located at distance 0). The closest the passenger car was to the barrier was 5.7 ft (Scenario 17: shoulder was 1.5 ft, lane was 11.5 ft, and buffer was 5 ft). Even when shoulder width equaled the buffer width (3 ft, see Scenario 7), drivers did not center their vehicle within the space; the vehicle was 1.3 ft to the right of the center of the lane. A logical combination of widths resulting in the passenger car being nearest the center of an 11-ft lane for the scenarios represented in Figure 22 is when the shoulder width is 4 ft and buffer width is 3 ft (see Scenario 3).

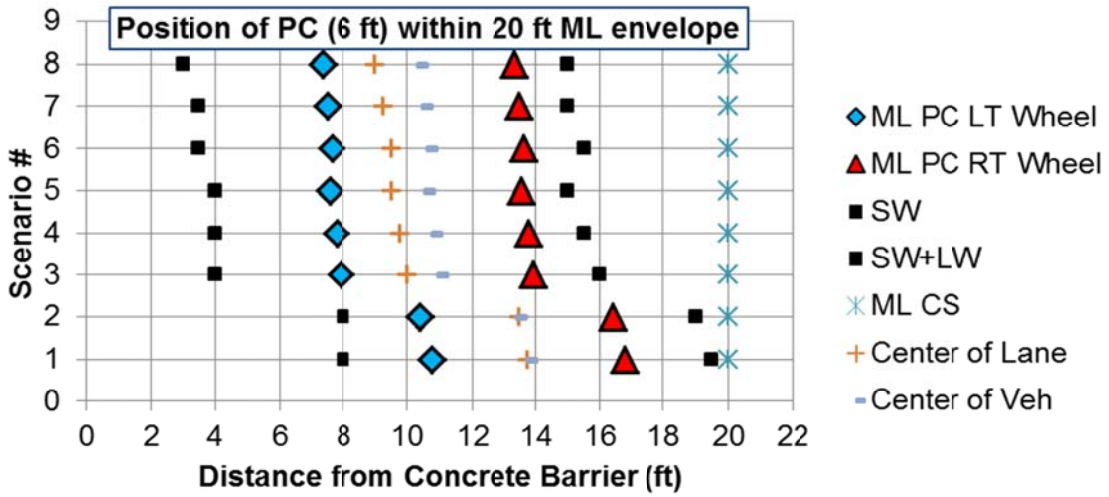


Source: TTI

Figure 22. Position of vehicle within 18-ft managed lane envelope.

Figure 23 shows 6-ft passenger car position when 20 ft is available for the managed lane cross-section. This example was selected to illustrate the value of a near-full-width shoulder. Scenarios 1 and 2 have the center of the vehicle near the center of the lane. For this group of scenarios, Scenarios 1 and 2 are the only combinations where that occurs—all other combinations have the center of the vehicle to the right of the center of the lane. This finding could be an illustration that at least an 8-ft shoulder is needed for drivers to be minimally influenced by the nearness of the concrete barrier.

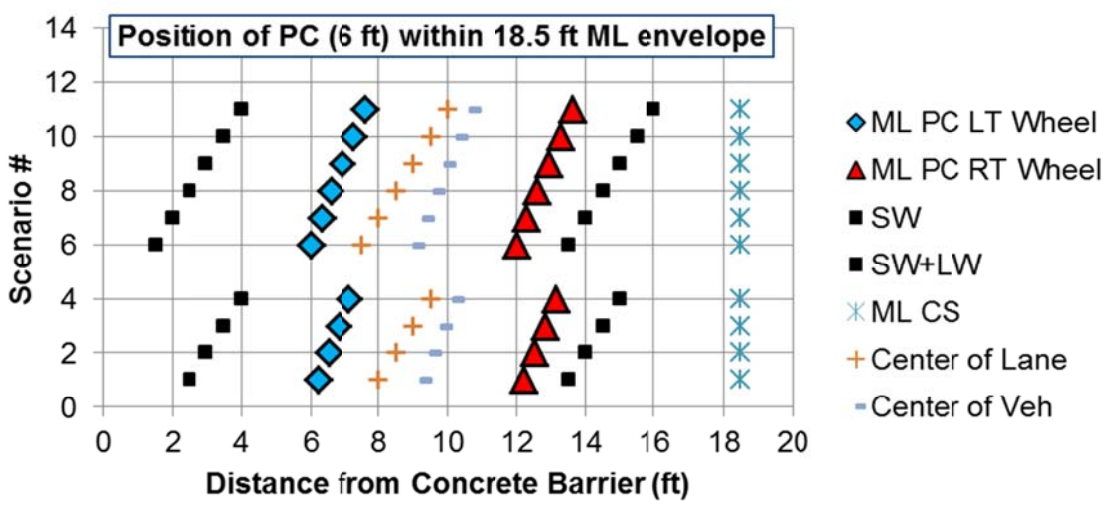
Comparing the plots for the 18-ft managed lane envelope (Figure 22) and 20-ft managed lane envelope (Figure 23) reveals that motorists prefer to drive closer to general-purpose traffic than the concrete barrier even with the extra 2 ft of cross-section. The closest the vehicle was to the barrier within a 20-ft managed lane envelope was almost 8 ft. Even when shoulder width equaled buffer width (4 ft, see Scenario 3 in Figure 23), drivers did not center their vehicle within the space. The vehicle was 0.9 ft to the right of the center of the lane.



Source: TTI

Figure 23. Position of vehicle within 20-ft managed lane envelope.

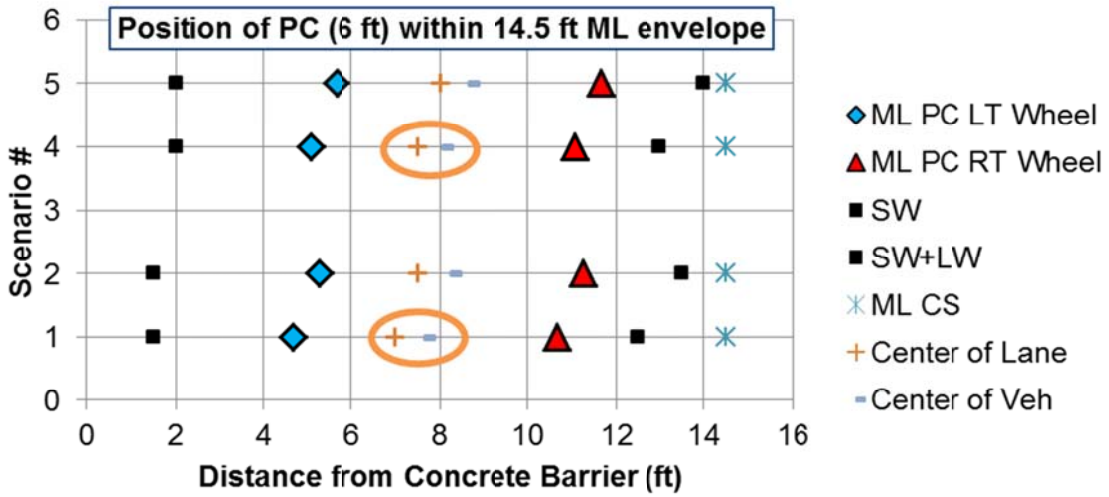
Figure 24 shows the predicted positions for a 6-ft passenger car within an 18.5-ft managed lane envelope. It was developed to illustrate the consequences of a minimal shoulder width. The top group of data is for 12-ft lanes, while the bottom half is with 11-ft lanes where the extra foot is given to the buffer width. Looking at the bottom row of data for each group, one can see the greatest difference between the position of the center of the vehicle and the center of the lane. Drivers are not comfortable being so close to the concrete barrier and are driving closer to the lane line to compensate. As the shoulder width becomes larger, the drivers still maintain some separation from the edgeline; however, that separation distance decreases as the shoulder width increases. The plots of these scenarios support the idea that the buffer width should not exceed the shoulder width. In addition, it indicates that if extra space is available, it should be used for the shoulder rather than the buffer.



Source: TTI

Figure 24. Lane position of passenger car within 11- or 12-ft managed lane.

Figure 25 was generated to investigate whether it is better to have a 12-ft lane and 1-ft buffer or an 11-ft lane and 2-ft buffer. The predicted lateral positions result in the driver positioning the vehicle slightly closer to the center of the lane when the extra foot is given to the buffer rather than the managed lane, as emphasized in Figure 25 with the orange circles.



Source: TTI

Figure 25. Lateral position of passenger car for 11- or 12-ft managed lane.

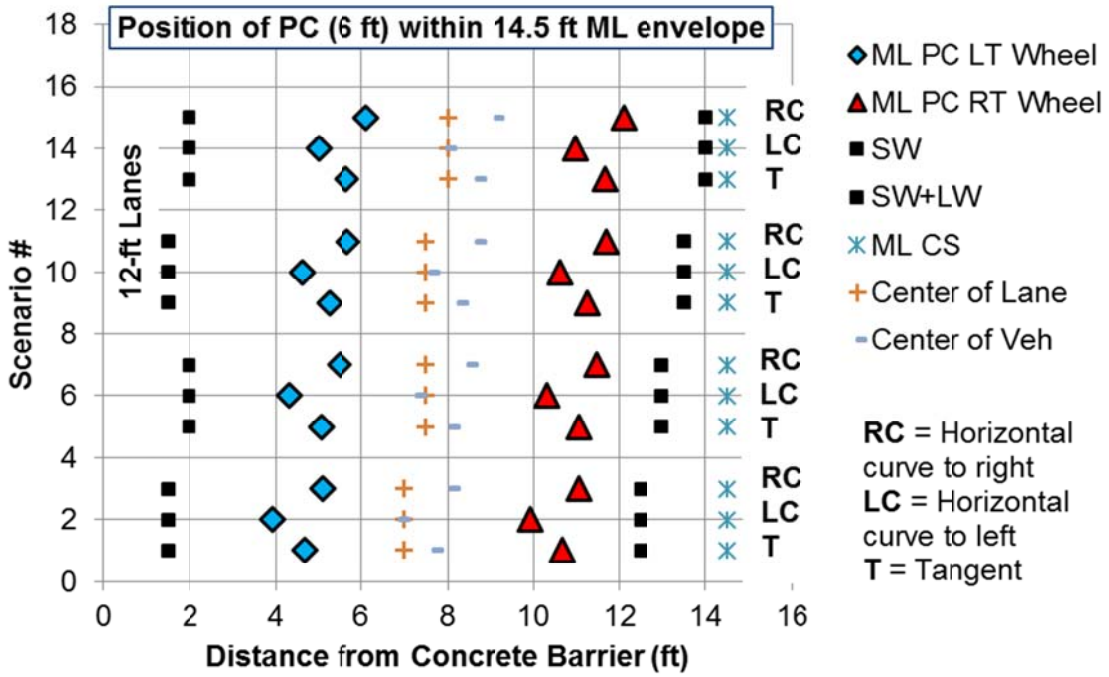
Figure 26 shows the lateral position of a passenger car within an 11- or 12-ft managed lane when the vehicle is on a curve to the right, a curve to the left, or a tangent section. As illustrated, drivers consistently position themselves closer to the lane line on curves to the right, closer to the edgeline on curves to the left, and in between on tangents.

MANAGED LANE PRACTITIONER FOCUS GROUP 2

Methodology—Second Session

The second focus group was conducted on July 22, 2015, for two hours. Eleven individuals participated in the focus group, representing nine different agencies—seven state departments of transportation, one regional congestion management agency, and one metropolitan planning organization. The agenda for the second focus group session consisted of the following:

- Introduction of focus group procedures and protocols.
- Overview of webinar presentation and discussion format.
- Presentation of the NCHRP 15-49 study overview.
- Presentation of the impacts of design findings from Study 5R.2.
- Discussion on agency preferences for design trade-offs.



Source: TTI

Figure 26. Illustration of effect of horizontal curvature on lateral position.

Focus Group 2 Discussion Topics

In the second focus group, the research team focused explicitly on reactions and guidance in light of findings from Study 5R.2. Questions included:

1. What does the data analysis reveal to you regarding shoulder, buffer, and lane widths?
2. What factors should influence the decision process?
3. Does previous guidance reflect these factors, and does it reflect them appropriately?
4. Are there any other observations regarding the data analysis?
5. Based upon our discussion today, what suggestions would you offer for national guidance on making design trade-offs between shoulder, buffer, and lane widths?

Focus Group 2 Findings

Practitioners highlighted three key questions that remained unanswered by the Study 5R.2 analysis:

- What is the effect of lane position on crash rates, travel speeds, and other operational metrics? The literature review revealed little empirical evidence of the relationship between lane position and these factors. However, the premise behind the analysis is that increasing vehicular lateral position toward the inside (left) shoulder or having the vehicle in the middle of the managed lane yields a preferential position because it incrementally reduces the likelihood of a crash or other impact due to vehicular proximity between the managed lane and the leftmost general-purpose lane.

- What is the impact of different access types on lane position? The Study 5R.2 analysis pertained to buffer-separated facilities; continuous-access managed lanes were explicitly not considered. Furthermore, the effect of dedicated ingress, egress, or weave lanes versus weave zones (without dedicated lanes for access) was not considered. The Study 5R.3 panel indicated that these points of comparison are desirable in order to draw additional conclusions on cross-section trade-offs.
- What are the impacts on the general-purpose lanes as a result of managed lane trade-offs? Practitioners noted that their agencies must consider all corridor users and configurations. Whereas inside shoulder preservation is indicated to be preferential to buffer width preservation, there was no comparative analysis presented that showed what effect this decision would have on the users of the leftmost general-purpose lane. As noted by practitioners, the inside shoulder is no longer available for use by disabled vehicles within the general-purpose lanes on corridors with concurrent-flow, non-barrier-separated managed lanes. Furthermore, even if the cross-section involved a 2-ft inside shoulder, 12-ft lane, and 12-ft buffer, the buffer would be utilized as a general-purpose or managed lane refuge, and that could be worse for safety and operations. Ultimately, if cross-section decisions yield detrimental operational or safety impacts in the general-purpose lane, then more significantly detrimental impacts could result given the position of the general-purpose lane relative to the entire cross-section. For example, a broken-down vehicle in the leftmost general-purpose lane will invariably degrade level of service in not only that lane but the adjacent general-purpose and managed lanes as well.

Despite the unanswered questions, practitioners broadly identified two scenarios from which to interpret results and establish preferences for design trade-offs. The first scenario involved construction of managed lanes within a new or reconstructed corridor without a highly constrained environment. Conversely, the second scenario envisioned such a constrained environment, where the ability to construct to design guidelines are highly compromised.

Across both scenarios, practitioners confirmed the importance of maintaining an adequate shoulder width. Quantitative data provided by Study 5R.2 conforms to the preferences revealed in the Study 5R.3 survey concerning trade-offs. Furthermore, this information lends credence to practitioner preferences toward reducing lane width in order to preserve the shoulder and buffer widths.

However, the second scenario of a highly constrained environment without preexisting HOV lanes yields corridors where the use of the corridor by drivers was designed for general-purpose operations, without advanced consideration of the provision of managed lanes. Providing new managed lanes within these sections is problematic, and options will be similarly constrained despite the analytics. Previous guidance has used language such as "avoid" and "minimum"—words that do not provide flexibility or the ability for practitioners to design to local conditions. Instead, practitioners expressed a preference for words such as "consider" and "evaluate" for use in highly constrained environments.

Based on comments regarding both scenarios, practitioners were expressly asked whether agencies would benefit more from a step-by-step process like AASHTO or a holistic approach

that yields flexibility and considerations for trade-off decisions. Practitioners indicated that both approaches can be useful. In particular, the step-by-step approach as illustrated by current Caltrans and AASHTO guidance is easier for agencies to follow and should be the first point of analysis for facilities falling under the first implementation scenario (new or reconstruction). However, for highly constrained environments as envisioned in the second scenario, creativity and flexibility are necessary and valued allowances. As such, additional guidance should be issued that supplements the step-by-step process with a holistic approach in these situations. The Study 5R.2 analysis yields different implementation scenarios by available pavement space, which could be the basis for a more holistic structure: "If you have *x-y-z* ft available, then implement *a-b-c* cross-section."

FREEWAY SAFETY RESEARCH

While the crash history for the sites used in this operational study were not researched (and probably represent too small of a sample size for definitive conclusions), information available in the literature can provide additional insights into trade-offs for cross-section dimensions. This section presents a summary of recent freeway safety research.

A 2013 paper (*13*) reported on an evaluation of the relationship between cross-section design (i.e., lane width, shoulder width, and buffer width) and safety performance for HOV lanes. The authors used three years (2005 to 2007) of crash data for 13 southern California segments totaling 153 mi (246.2 km). The segments were buffer-separated between the HOV lanes and the general-purpose lanes. Crashes included those that occurred on the median shoulder, in the HOV lane, or in the adjacent general-purpose left lane. Independent variables included geometric attributes and annual average daily traffic (AADT). The authors made the following observations regarding geometric cross-section and crashes:

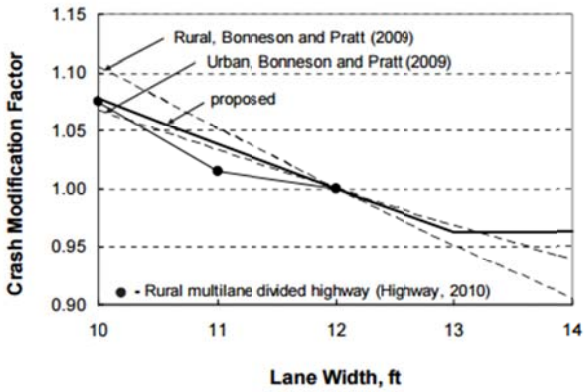
- **HOV lane width**: A wider HOV lane width tends to be associated with lower crash frequencies except for the case with a width of 13 ft, which was attributed to not having enough segments with 13-ft widths to be able to draw a conclusion.
- **AADT**: Higher AADTs in HOV and left lanes, except injury crashes in the left lane, are positively related to crash frequency, which means that freeway segments with more traffic tend to have higher crash frequencies. However, injury crashes in the left lane show an opposite, negatively correlated pattern, albeit by a very small number. This implies that more traffic leads to fewer crashes in the left lane, but the variation is not substantial. The causal effect was not investigated in the study, but the authors offered a potential interpretation that crashes are likely to be more severe when traffic is light due to the likely higher speeds inherent in lower traffic density.
- **Shoulder width**: The evaluation indicated that wider shoulder width helps reduce crashes in HOV lanes.
- **Buffer width**: Coefficients for buffer widths were not found to be statistically significant at the 10 percent level.
- **Left lane width**: Left lane widths were excluded in the estimated model due to their statistical insignificance (i.e., large standard errors); no inference could be drawn.

The authors also provided case study examples of preferred cross-section allocation if converting a section from an HOV lane and left shoulder to a section having a buffer, HOV

lane, and left shoulder. In all examples, the authors recommended the inclusion of a buffer by reallocating some of the shoulder width to the buffer.

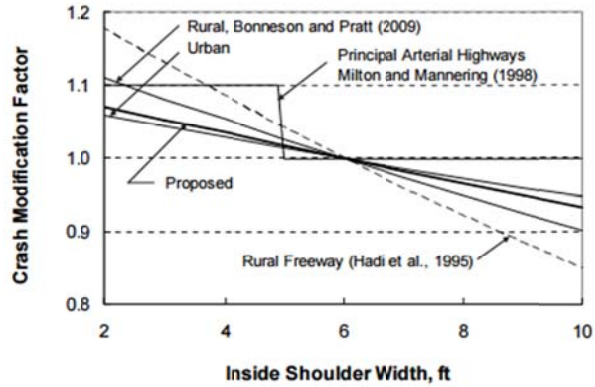
The *Highway Safety Manual* (HSM) (*14*) now includes predictive methods for freeways. The developed chapters were based on research conducted as part of NCHRP 17-45 (*15*). The researchers found that reductions in lane widths and inside (left) shoulder widths are associated with increased crashes. The proposed crash modification factor for the HSM along with the findings from other recent work is shown in Figure 27 for lane width and Figure 28 for inside (left) shoulder width. The range of shoulder widths included in the NCHRP 17-45 study was 2 to 12 ft. An inside shoulder width of 6 ft was assumed as the base condition. Some agencies avoid inside shoulder widths greater than 4 ft and less than 8 ft because of concerns that drivers may attempt to seek refuge in a space that does not have sufficient width to accommodate a typical passenger vehicle (6 ft) plus clearance (desirably 1 to 2 ft, as discussed in the *Green Book* (*7*), Section 4.4.2, pp. 4–10).

A recent Texas Department of Transportation (TxDOT) project (*16*) that examined the trade-offs of reducing lane and shoulder widths to permit an additional freeway lane also identified increased crashes when the widths of lanes or shoulders are reduced. The research also revealed, however, that an additional lane can result in reductions in crashes. Whether the benefits of the additional lane completely offset the consequences of the reduced lane and shoulder widths would depend on the conditions present at the site. The authors of the Texas study developed an equation and a spreadsheet that could be used to evaluate the trade-offs. Note that the Texas work focused on freeways with general-purpose lanes rather than freeways that include a managed lane.



Source: NCHRP 17-45 (*15*)

Figure 27. Proposed crash modification factor for lane width.



Source: NCHRP 17-45 (*15*)

Figure 28. Proposed crash modification factor for inside shoulder width.

A Florida study (*17*) developed crash prediction equations for freeways facilities with HOV and HOT lanes. The authors developed unique models by number of freeway lanes. Models were developed for 6-, 8-, 10-, and 12-lane freeways (number of lanes reflect both directions and include the managed lanes). For all the models, segment length and AADT were significant and included. For most of the models, left shoulder width was the only other

significant variable. An increase in left shoulder width was associated with decreases in crashes. The effect of buffer type on crashes was found to be statistically significant only in the model for 10-lane freeways. The inclusion of a 2- to 3-ft buffer was associated with fewer fatal and injury crashes.

The findings from the safety literature are clear in that reduction in left shoulder width is associated with increased number of crashes. Safety studies for general-purpose freeway lanes also have found that reduction in lane width is associated with more crashes. Some of the increases in crashes due to reduction in lane or shoulder widths could be offset if the reductions are due to including an additional freeway lane. The evaluations of the safety benefits of buffers are limited. For the two studies that included buffer within the evaluations (*13, 17*), there was only one case (on 10-lane freeways) when the variable was statistically significant. Limitations in sample size along with the distribution of the buffer widths available may be affecting the results.

SUMMARY/CONCLUSION

Two efforts were used to identify potential trade-offs in cross-section dimensions—gathering the lateral position of vehicles in the field within the managed lane with different shoulder, lane, and buffer widths and moderating discussions among practitioners regarding cross-section dimension priorities. An online survey and two webinar focus groups were used for the practitioner discussions. The field studies included data collected at 28 sites using fixed video cameras and along 161 centerline miles using an instrumented vehicle that recorded data for the vehicle immediately in front of the instrumented vehicle. The key measure was lateral position of the managed lane vehicle measured between the shoulder edgeline and the left rear wheel. The variables that affected lateral position included the following:

- Vehicle type—Larger vehicles, such as buses, were closer to the shoulder edgeline, and smaller vehicles, such as motorcycles, were a greater distance away.
- Presence of a vehicle in the neighboring general-purpose lane—Vehicle presence in the general-purpose lane resulted in the managed lane vehicle shifting closer to the shoulder edgeline.
- Pylons—Managed lane drivers shifted away from the pylons placed in the buffer.
- Horizontal alignment (tangent or curve) and the direction of the horizontal curve (left or right).
- Left shoulder, lane, and buffer—The best statistical model used a parabolic curve to model the relationships, resulting in smaller values for those elements having greater influence on the lateral position. For example, modifying a 6.5-ft shoulder to a minimum shoulder (i.e., 1.5 ft) will result in drivers moving to the right about 0.5 ft; however, if an 18.5-ft shoulder is reduced by 5 ft, the impact in operations is negligible (drivers will shift only about 0.11 ft toward the right).

The speed of the lead vehicle for the data collected using the instrumented vehicle was also considered; however, it was found to not be significant for this dataset. The variable concerning types of access to the managed lane was considered but found to not be significant. Another variable considered but found to not be significant was an estimate of whether the managed lane vehicle was more than 10 mph faster than the neighboring general-purpose lane vehicles.

Finally, an equation was developed that can be used to predict the lateral position of a vehicle within the managed lane.

Key findings from the two research studies along with information available in the literature include the following:

- The maintenance of adequate shoulder width is desirable.
- The practice of reducing the lane width by 1 ft (from 12 ft to 11 ft) and providing that foot of width to the buffer is appropriate.
- Drivers shy away from the concrete median barrier. Research findings indicate that lateral position is highly affected for narrow shoulder widths.
- The use of pylons affects lateral position. Using the pylons within a wider buffer can offset the impacts on lateral position.
- As expected, a driver's lateral position is affected by horizontal curvature.
- The impact on lateral position is greater within the minimal values for shoulder, lane, and buffer widths. For example, a 1-ft reduction in shoulder width results in greater changes in lateral position when the shoulder width is near minimal values (e.g., 2 or 4 ft) as compared to when the shoulder width is near desirable (e.g., 8 ft or 14 ft).
- Research findings from recent safety research indicate that—in general—the left shoulder width should be reduced before the general-purpose lane right shoulder width. Safety research also indicates that it is better to reduce a shoulder width by 1 ft prior to reducing a lane width by 1 ft; however, it could be different depending on site conditions. Tools, such as the *Highway Safety Manual* (*14*) and associated spreadsheet or the equation (and spreadsheet) developed as part of a recent TxDOT project (*16*), are available to help predict crashes for freeway segments, and these tools should be used to evaluate the trade-offs for different freeway general-purpose lane cross-section decisions.
- Practitioners would like to have a step-by-step process like what is currently included in the AASHTO HOV guide (*3*) as an example; however, recent findings from safety research indicate that any reduction in freeway shoulder or lane width is associated with increased crashes. For general-purpose lanes, a 1-ft reduction in lane width is associated with greater increase in crashes than a comparable 1-ft reduction in shoulder width; however, rarely is a cross-section decision just a decision about a single foot. Trade-offs between different cross-section options need to be evaluated to determine the optimal design.

CHANGES TO PRACTICE

Based on the findings from the two studies, the following changes to practice can be considered:

- The practice of reducing the lane width by 1 ft (from 12 ft to 11 ft) and providing that foot of width to the buffer is appropriate.
- Drivers shy away from the concrete barrier. The use of minimal width for the left shoulder results in managed lane drivers being closer to the general-purpose vehicles. A buffer can offset this impact.

- Consider providing additional buffer or shoulder widths within horizontal curves since drivers are shifting their lateral positions when driving on a horizontal curve, especially horizontal curves to the left.
- Consider the buffer width when using pylons. Drivers shift away from the pylons, and a wider buffer can be used to offset this behavior.
- If insufficient space is available for a full-width left shoulder, consider splitting the available width between the left shoulder and a buffer. Managed lane vehicles are closer to the center of the lane when these values are similar.

CHAPTER 4

OPERATING SPEED ON A BUFFER-SEPARATED MANAGED LANE

BACKGROUND ON SPEED PREDICTION

Previous research on operating speed has identified factors that influence the speed of individual vehicles. These factors are used to predict operating speeds, which are then used as measures of roadway consistency and driver expectancy. As documented in the TRB's *Modeling Operating Speed: Synthesis Report* (*18*), several factors influence operating speed, with most studies focusing on how horizontal curvature influences the free-flow speed selected by roadway users. For example, for rural two-lane highways, studies by Krammes et al. (*19*), Fitzpatrick et al. (*20*), and Schurr et al. (*21*) developed speed prediction equations for horizontal curves that included characteristics of the horizontal curve (e.g., degree or radius of curve, length of curve, deflection angle) and tangent speed (e.g., the measured or assumed 85th percentile speed or the posted speed limit). Additionally, some studies (*20*, *22*) report that vertical alignment has a significant impact on speeds, especially those of heavy vehicles.

A study on rural four-lane highways in Kentucky (*23*) developed a speed prediction model that included consideration of lane (inside or outside), horizontal curve length or radius, and indicator variables for shoulder type (surfaced), median barrier presence, pavement type (concrete or asphalt), approaching section grade, and curve presence on approach. Himes and Donnell (*24*) also found different speeds in the left and right lanes for rural and urban four-lane highways and identified the following variables as relevant to their study: heavy vehicle percentage, posted speed limit, and adjacent land use.

Because horizontal curves have such a notable effect on operating speed, the available literature is greater for that roadway feature. A few studies have attempted to predict speeds on tangents, including work by Polus et al. (*25*) and Donnell et al. (*22*). Polus et al. considered tangent length and the previous and following curve radii including grouping the radii into different categories in their attempts to develop usable speed prediction equations. Donnell et al. used a combination of field data and simulation-generated data. Predicting truck speed prior to a horizontal curve was a function of radius of curve, length of approach tangent, grade of approach tangent, and length of the approach tangent-radius interaction term.

The *Highway Capacity Manual* (HCM) (*26*) provides methods for estimating free-flow speed (FFS) on freeways and highways; however, the source of those methods is not obvious. The HCM establishes that a direct relationship exists between number of lanes and capacity. This relationship implies a similar connection between number of lanes and level of service. Particularly for freeway sections of 12-ft lanes, the manual establishes that the FFS is negatively impacted when reducing the lane width, but it is unaffected when increasing the lane width. For operational analyses, HCM Exhibit 11-8 establishes that FFS should fall about 2.0 mph if the width reduction is 1 ft or less, and 6.6 mph if the width is reduced to the range of 10–11 ft. Regarding the effect of reducing the right-side clearance, the HCM establishes an FFS reduction ranging from 0.0 up to 3.6 mph, depending on how big the reduction is

compared to the base condition of 6 ft, as well as the number of lanes in one direction. The extreme case of a 3.6-mph FFS reduction corresponds to no right-side clearance at freeway sections of two lanes in one direction. According to the HCM, a freeway segment with two 10-ft lanes and no right-side clearance is expected to have an FFS reduction of 10.2 mph compared to a segment with two 12-ft lanes and 6 ft of right-side clearance.

A Texas study (*27*) generated speed prediction equations for freeways with posted speed limits up to 80 mph and multilane highways with posted speed limits up to 75 mph (see Table 23). Those equations were used to develop suggested procedures for calculating free-flow speed on freeways and multilane highways that could be considered for a future edition of the *Highway Capacity Manual*. Lane width was considered in the statistical evaluations; however, the variable was found to not be significant, probably because of the very limited range of widths available in the dataset.

Table 23. Texas free-flow speed equations for high-speed highways.

Element	Four-Lane Limited Highways (Freeways)	Four-Lane Nonlimited Highways
Free-Flow Speed Equation	$M\_FFS_{4L\text{-}L}$ = 71.5226 − 7.1769 x PSL[65] − 4.6514 x PSL [70] − 3.5231 x PSL [75] − 0.1106 x Ramps_Pts − 2.8641 x Per_Trks + 3.0688 x Lane [inside] + 0.01012 x MW + 0.3893 SW_L + 4.4638 Vehicle [car]	$M\_FFS_{4L\text{-}NL}$ = 64.9684 − 2.1535 x PSL [65] − 1.3004 x PSL [70] − 0.0266 x Down_HC_A + 2.8156 x Lane inside + 0.0071 x MW + 1.5127 x SW_L − 0.4058 x SW_R + 1.8900 x Light [day] + 3.4556 x Vehicle [car]
Base Values	PSL (mph) = 80, Ramps_pts = 0, Per_Tkrs = 0, Lane = outside, MW (ft) = 0, SW_L (ft) = 0, Vehicle = Truck	PSL (mph) = 75, Lane = outside, MW (ft) = 0, SW_L (ft) = 0, SW_R (ft) = 0, Vehicle = Truck, Light = Night, Down_HC_A = 0
Variable Definitions for Both Equations	*Down_HC_A* = angle of next horizontal curve downstream of site. *Lane[inside]* = 1 when vehicle is on inside (or left) lane, 0 if vehicle is on outside (or right) lane. *Light[day]* = 1 when light condition is daytime, 0 if light condition is nighttime. $M\_FFS_{4L\text{-}NL}$ = predicted mean free-flow speed for four-lane nonlimited access site (mph). $M\_FFS_{4L\text{-}L}$ = predicted mean free-flow speed for four-lane limited-access site (mph). *MW* = median width (ft). *Per_Trks* = percentage trucks present in decimal equivalent for hour. *PSL[65]* = 1 when posted speed limit is 65 mph, 0 otherwise. *PSL[70]* = 1 when posted speed limit is 70 mph, 0 otherwise. *PSL[75]* = 1 when posted speed limit is 75 mph, 0 otherwise. *Ramps_Pts* = number of ramp gores within 3 mi upstream or downstream of site for direction of travel. *SW_L* = left shoulder width (ft). *SW_R* = right shoulder width (ft). *Vehicle[car]* = 1 when the vehicle type is car, 0 if the vehicle type is truck.	

Source: Information compiled by research team from Robertson et al. (*27*).

Also in Texas, Cooner and Ranft (*28*) examined the safety of buffer-separated HOV lanes at I-35 East and I-635 in the Dallas area. These lanes were implemented by reducing travel lane width and converting the inside shoulder to an HOV lane. They evaluated the operational impact by measuring the speed differential between the HOV and the rest of the lanes. Both sections in the analysis had an increase in crash rates after the implementation of HOV lanes.

The increase in crashes concentrated in the HOV lane and it most adjacent lane. The researchers linked this increase in crashes to the differential of speed between the two lanes. They recommended a buffer between the HOV and general-purpose lanes, such that the right shoulder, the HOV lane, and the buffer add up to 18 ft at least.

Another Texas study (*16*) investigated the operational implications of using reduced lane and shoulder widths on freeways. The authors developed an equation that can be used to predict speeds per lane for freeway locations with boundary conditions similar to those present in the study database (see Table 24). The analysis found speeds 2.2 mph higher for a 12-ft lane as compared to an 11-ft lane. The HCM includes adjustments to the freeway free-flow FFS speed for lane width and right-side lateral clearance. The result of this Texas study indicated that the reduction in FFS is slightly greater for 11-ft lanes (2.2 mph) than the value currently in the HCM (1.9 mph).

Table 24. Texas freeway mean operating speed predictive equation.

Condition	Equation and Variable Definitions
Equation	$S = [67.80 - 0.00018(V^2) + 4.60(\mathrm{MedType_{Grass}}) + 2.21(\mathrm{LaneW}) + 3.62(\mathrm{ToLeft_{B+P}}) + 2.03(\mathrm{ToLeft_{Shld}}) - 3.89(\mathrm{ToRight_{SCL}}) - 4.39(\mathrm{ToRight_{Shld}}) - 2.00(\mathrm{NLight}) - 1.47(\mathrm{DayofWeek})]$
Variable Definitions	S = estimated mean operating speed per lane for a five-minute time period (mph). $V = V_{5\text{-}min\,/lane}$ = the five-minute traffic volume for the freeway lane of interest (vehicles/five minutes). $MedType_{Grass}$ = value of 1 if grass median, otherwise 0. $LaneW$ = lane width (ft). $ToLeft_{B+P}$ = value of 1 if buffer plus pylons located to left of lane, otherwise 0. $ToLeft_{Shld}$ = value of 1 if shoulder located to left of lane, otherwise 0. $ToRight_{SCL}$ = value of 1 if speed change lane located to right of lane, otherwise 0. $ToRight_{Shld}$ = value of 1 if shoulder located to right of lane, otherwise 0. $NLight$ = value of 1 if nighttime conditions, otherwise 0. $DayofWeek$ = value of 1 if Wednesday (representing weekday), otherwise 1 (weekend).
Boundary Conditions	Applicable to freeway corridors with the following: • $0 \le V_{5\text{-}min\,/lane} \le 250$. • Lane width rounded to 11 ft or 12 ft. • 2 ≤ Number of Lanes ≤ 5. • 4.0 ft ≤ Right Shoulder Width ≤ 20.0 ft. • 1.5 ft ≤ Left Shoulder Width ≤ 23.0 ft. • 6.0 ft ≤ Median Width ≤ 125.0 ft. • 60 mph ≤ Posted Speed Limit ≤ 70 mph.

Source: Information compiled by research team from Dixon et al. (*16*).

Previous studies on high-speed facilities demonstrate that volume, lane width, and shoulder width may be influential on the operating speed. The potential effects of buffer width, especially buffers with pylons, have not yet been investigated.

OBJECTIVE

The objective of the speed study conducted in Phase II of this project was to identify the factors that influence operating speed in a buffer-separated managed lane. Factors considered included the managed lane volume, left shoulder width, managed lane width, buffer width and type, and operating speed in the neighboring general-purpose lanes.

SITE SELECTION

To be able to identify whether the managed lane geometrics influence operating speed, a range of geometric design features for both managed lanes and general-purpose lanes are needed. For this study, initial sites were selected from the data collection sites where lateral position data (see Chapter 3) were gathered in Dallas, Texas; Los Angeles, California; and Orange County, California. The sites surveyed during the lateral position study showed a variety of shoulder widths, lane widths, and buffer widths. Sites in Dallas also had pylons within the buffer. All of these sites had one managed lane operating 24 hours a day, seven days a week that were separated from the general-purpose lanes with a flush buffer.

In Texas, TxDOT maintains permanent sensors along several freeways. The locations of those sensors in Dallas were provided to the research team. Several sites were selected where a nearby access opening to the managed lane was not present. For sites in Dallas, Texas, speed data were collected from:

- I-635 @ Greenville.
- I-635 @ Miller.
- I-635 @ Skillman.
- I-635 @ Centerville.
- I-635 @ Oates.
- US-67 @ Red Bird.
- US-75 @ Legacy.
- US-75 @ Midpark.
- US-75 @ Parker South.
- US-75 @ Ridgemont.
- US-75 @ Spring Valley.

Highway US-67 was not part of the lateral position study but was added because it was the only site that did not deploy pylons as a buffer separator in Dallas. For each of the locations listed above, the speed per direction was considered. Therefore, in Dallas, 22 unique sites were available for analysis.

In California, the highways surveyed were:

- SR 134.
- I-105.
- I-210.
- I-405.

The Caltrans Performance Measurement System (PeMS) database was used to obtain speed data at various points along each of these four highways. Sites with no nearby entry/exit point

to the managed lane were considered. On SR 134, data were collected between Milepost 0 and 13 at 14 different locations. On I-105, data were collected at 16 different locations between Milepost 2 and 16. On I-210, data were collected at 26 stations located between Milepost 26 and 52. For I-405, data were collected between Milepost 0 and 48 at 53 different detector stations. Speed and geometric data for a total of 109 California sites were available for the analysis.

GEOMETRICS

Table 25 provides a description of the geometric variables collected and considered for the analysis. The variable names included the term HOV rather than managed lane for the managed lane because the California PeMS uses the term ML for mainlanes and HOV for the buffer-separated lane. The research team decided to maintain consistency between the speed data and the geometric data. Information for the variables was gathered by using the measurement tool available in Google Earth. Measurements for lane width, shoulder width, and buffer width in general were made between the centers of the pavement lane markings or to the edge of the pavement for shoulder width. The accuracy of the measurement depended on the quality of the aerial view, and the quality did vary for the sites. The research team estimated that the accuracy of the measurements was on the order of about 0.5 ft. The posted speed limit information was acquired by using the StreetView feature available in the Google Earth suite of tools.

Table 25. Description of geometric variables.

Variable Name	Description
HOV_SW	Managed lane, left shoulder width (ft)
HOV_LW	Managed lane, lane width (ft)
HOV_BW	Buffer width (ft)
Buf_Type	Buffer type between managed lane and general-purpose freeway lanes—either pylons or flush
#GP	General-purpose lanes, number of general-purpose lanes that are not barrier-separated and are moving in same direction
GP_Adj_LW	General-purpose lanes, width of lane adjacent to the managed lane (ft)
GP_Avg_LW	General-purpose lanes, average lane width (ft)
GP_SW	General-purpose lanes, right shoulder width (ft)
PSL	Posted speed limit (mph)

Table 26 provides the number of sites per freeway direction along with the number of general-purpose lanes and posted speed limit for the California freeways. Table 27 shows the range of the measured geometrics for the sites in California. Because each freeway included several sites, the minimum, maximum, and average values are listed. Lane widths varied between 10 and 12 ft. None of the California highways for this study used pylons as a separator between the general-purpose and managed lane traffic. Buffer width on I-405 varied between 1 and 13 ft, while on all other highways, it varied between 1 and 5 ft. The variety in buffer widths is in part due to the different combinations of pavement markings that outline the buffer area. In general, California uses yellow and white pavement markings. Figure 29 shows one example of pavement markings used to mark the buffer between a managed lane and general-purpose lanes.

Geometric characteristics for Dallas are presented in Table 28. Shoulder width values represent a range of 1.2 to 7.4 ft. Highways I-635 and US-75 use pylons to separate the managed lane from the general-purpose lanes. Figure 30 shows an example of pylons being used on a Houston, Texas, freeway. Sites on US-67 use double white pavement markings to separate traffic between the managed lane and general-purpose lanes. Sites with pylons had a buffer width between 4 and 5 ft, whereas sites without pylons had a measured buffer width of 3 ft. In Dallas, I-635 and US-75 have a minimal shoulder on the left, while US-67 has a shoulder width of more than 7 ft for the managed lane. All lane widths ranged between 10- and 12-ft wide. The posted speed limit ranged between 60 and 70 mph.

Table 26. California freeway characteristics.

Hwy	Dir	#Locations	PSL	#GP
I-105	EB	8	65	5
I-105	WB	8	65	5
CA-134	EB	8	65	4
CA-134	WB	6	65	4
I-210	EB	14	65	4
I-210	WB	12	65	4
I-405	NB	26	65	5
I-405	SB	27	65	5

Note: Column headings:

- Hwy = highway number.
- Dir = direction of travel for the managed lane.
- #Locations = number of unique sites where speed data were obtained.

See Table 25 for description of other column headings.

Table 27. California measured geometrics.

Hwy	Dir	Rge	HOV SW	HOV LW	HOV BW	GP Adj LW	GP Avg LW	GP SW
I-105	EB	Avg	10.4	10.9	4.8	11.6	11.8	11.0
I-105	WB	Avg	10.0	11.4	4.9	11.4	11.8	13.4
CA-134	EB	Avg	2.9	11.2	1.5	11.1	11.0	8.5
CA-134	WB	Avg	1.3	11.3	1.7	11.1	11.1	12.1
I-210	EB	Avg	5.7	11.3	3.1	11.4	13.3	9.5
I-210	WB	Avg	4.6	11.3	3.0	11.4	11.4	8.6
I-405	NB	Avg	4.2	10.6	3.3	11.2	11.3	8.7
I-405	SB	Avg	3.9	11.0	2.8	11.2	11.3	10.0
I-105	EB	Max	13.0	11.5	5.0	12.0	12.0	21.5
I-105	WB	Max	20.0	12.0	5.0	12.0	12.0	28.5
CA-134	EB	Max	15.0	12.0	1.5	11.3	11.0	10.0
CA-134	WB	Max	2.0	11.5	2.0	11.5	11.3	30.0
I-210	EB	Max	20.0	12.0	5.0	12.0	12.0	14.0
I-210	WB	Max	19.0	12.0	5.0	12.0	12.0	15.0
I-405	NB	Max	12.0	11.5	13.0	12.0	12.0	14.0
I-405	SB	Max	12.0	12.0	12.0	12.0	12.0	18.0
I-105	EB	Min	8.5	10.5	4.5	11.5	11.5	9.0
I-105	WB	Min	6.5	10.0	4.5	11.0	11.5	8.5
CA-134	EB	Min	1.0	10.8	1.5	11.0	11.0	7.0
CA-134	WB	Min	1.0	11.0	1.5	11.0	11.0	7.0
I-210	EB	Min	1.0	11.0	2.5	11.0	11.0	8.0
I-210	WB	Min	1.0	11.0	2.5	11.0	11.0	1.0
I-405	NB	Min	1.0	10.0	1.0	10.5	11.0	1.0
I-405	SB	Min	1.0	10.0	1.0	10.8	11.0	2.0

Note: Column headings:

- Hwy = highway number.
- Dir = direction of travel for the managed lane.
- Rge = range of measurements taken (avg = average, max = maximum, min = minimum).

See Table 25 for description of other column headings.

Source: Fitzpatrick

Figure 29. Example of buffer in California.

Table 28. Dallas, Texas, measured geometrics.

Site	Dir	PSL[a]	HOV SW	HOV LW	HOV BW	Buf Type	#GP	GP Adj LW	GP Avg LW	GP SW
I-635 @ Centerville	SB	70	1.9	11.2	4.9	pylons	4	11.0	11.0	9.9
I-635 @ Centerville	NB	70	2.4	10.6	5.1	pylons	4	10.9	11.0	7.7
I-635 @ Greenville	EB	70	1.2	10.5	5.0	pylons	4	10.8	11.0	7.0
I-635 @ Greenville	WB	70	2.0	11.7	5.0	pylons	4	10.2	11.0	7.0
I-635 @ Skillman	EB	70	2.8	11.3	5.4	pylons	4	11.0	11.0	7.0
I-635 @ Skillman	WB	70	2.2	11.1	5.6	pylons	4	10.8	11.1	9.9
I-635 @ Miller	EB	70	2.0	11.0	5.0	pylons	4	10.7	11.0	10.0
I-635 @ Miller	WB	70	2.0	10.5	5.0	pylons	4	10.5	11.0	10.0
I-635 @ Oates	NB	70	2.0	11.0	5.0	pylons	4	10.5	11.7	7.0
I-635 @ Oates	SB	70	2.0	10.2	5.0	pylons	4	10.9	11.0	10.0
US-75 @ Legacy	NB	60	1.5	11.9	3.8	pylons	3	10.3	11.0	1.3
US-75 @ Legacy	SB	60	2.0	11.8	4.1	pylons	3	10.3	10.9	0.9
US-75 @ Midpark	SB	60	2.3	11.2	4.5	pylons	5	11.3	11.4	8.4
US-75 @ Midpark	NB	60	1.5	11.6	4.0	pylons	5	10.0	11.1	9.5
US-75 @ Parker	SB	60	2.0	11.0	4.0	pylons	4	10.5	11.0	10.0
US-75 @ Parker	NB	60	2.0	10.9	4.0	pylons	4	10.9	11.0	6.8
US-75 @ Ridgemont	NB	60	1.5	11.0	4.2	pylons	3	10.0	10.7	1.1
US-75 @ Ridgemont	SB	60	2.0	11.8	4.2	pylons	3	10.4	10.9	1.6
US-75 @ Spring	NB	60	2.0	11.4	4.6	pylons	4	10.5	11.0	9.5
US-75 @ Spring	SB	60	2.0	11.7	4.2	pylons	4	10.2	11.0	9.7
US-67 @ Red Bird	NB	65	7.3	10.6	3.0	flush	2	12.1	12.0	10.0
US-67 @ Red Bird	SB	65	7.4	11.1	3.0	flush	2	12.3	12.0	10.0

[a] See Table 25 for description of terms.

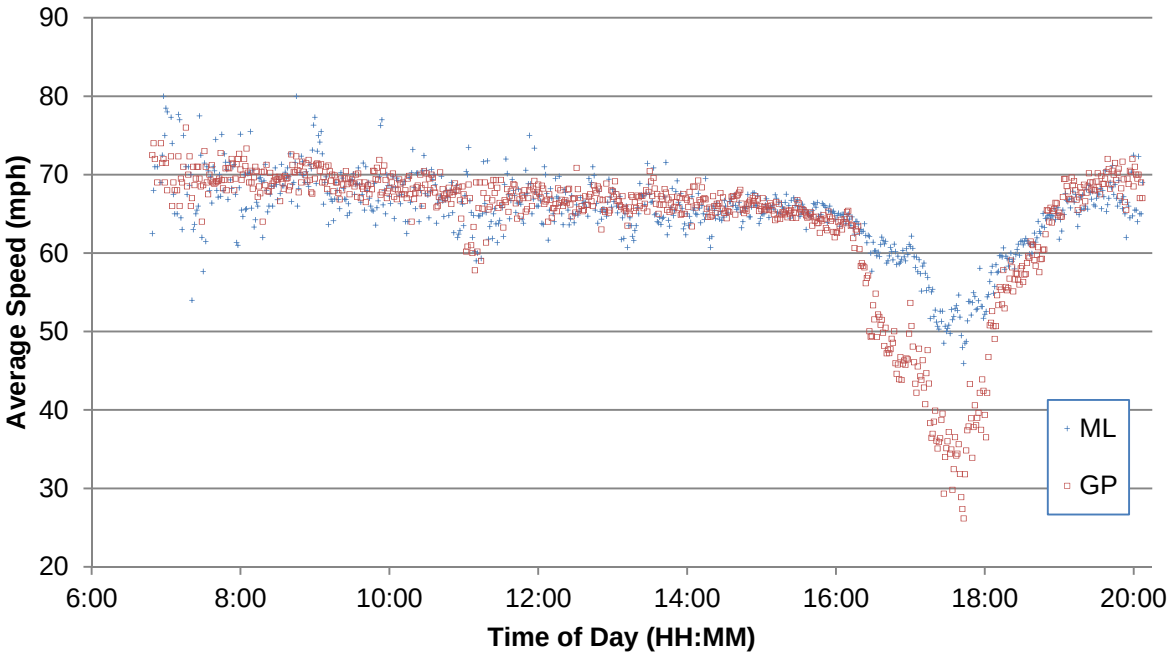
Source: TTI

Figure 30. Example of pylons on a Houston, Texas, freeway.

SENSOR DATA

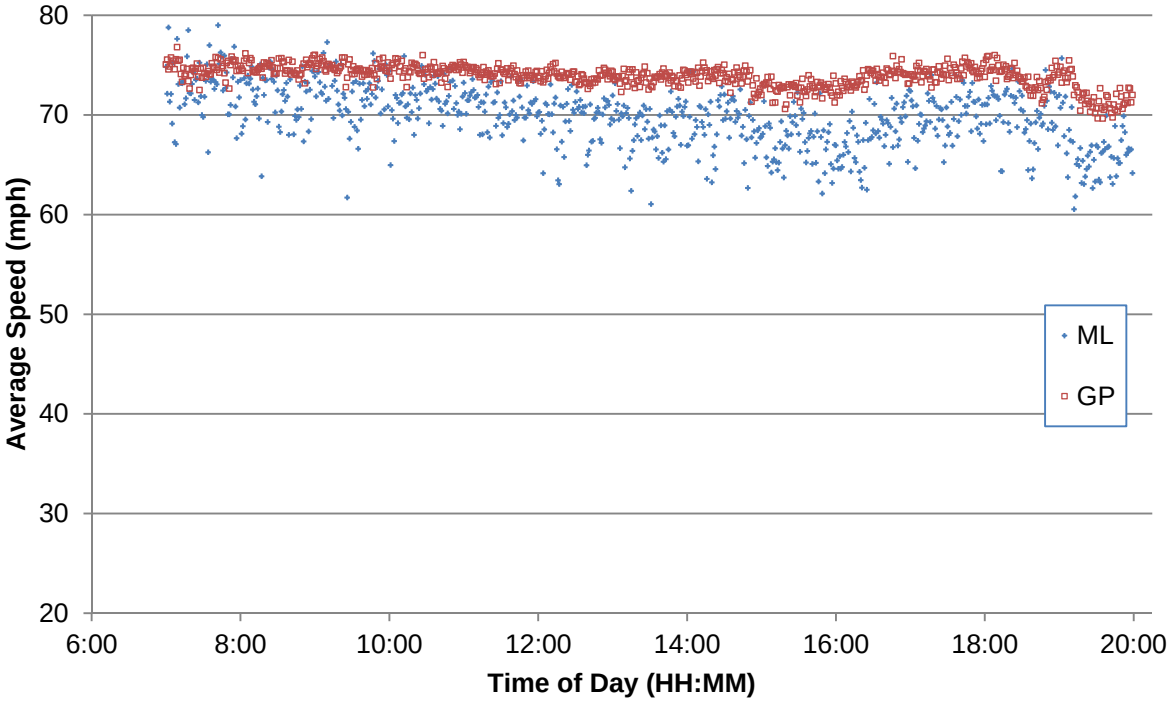
Speed and volume data were obtained from TxDOT or from the Caltrans PeMS website for data collected by permanent roadway sensors. The amount of speed data available from the permanent sensors was very large; therefore, the research team selected several days within each city to represent typical conditions.

Previous research (*16*) demonstrated that freeway speeds can vary by day of the week, so the research team conducted preliminary reviews to verify that certain days should or should not be used. A sample of managed lane data was used to generate speed by time plots. Figure 31 shows the speed according to the time of day for a Wednesday on I-635 EB and Figure 32 shows the speed according to the time of day for a Saturday at I-635 WB in Dallas. The posted speed limit is 70 mph for I-635. As shown in Figure 31, the speed in the managed lane was roughly equal to the speed in the general-purpose lane for the majority of the day, except in the afternoon between 4 and 7 p.m. During this period of time, the recorded speeds on the managed lane were faster than on the general-purpose lane. Figure 32, which represents a weekend day, shows that speeds were constantly between 70 and 75 throughout the day in the general-purpose lane. The managed lane motorists traveled at speeds below the speed limit throughout that Saturday. The volume data indicate that fewer motorists are using the managed lane facility on the weekend compared to the weekdays. Because of the lower managed lane volumes, the research team only used weekdays in this analysis of the speed data.



Source: TTI

Figure 31. Average speed by time of day on a Wednesday for I-635 EB, Dallas, Texas.



Source: TTI

Figure 32. Average speed by time of day on a Saturday for I-635 WB, Dallas, Texas.

For both Orange County and Los Angeles, three days per month were selected between September 2014 and August 2015, for a total of 36 days for the California dataset. The day of the week varied between Monday to Friday. For Texas, two days per month in 2014 were selected, for a total of 24 days for the Dallas dataset. In general, the second week of the month was selected to try to avoid major holidays.

For the sites in Texas, the research team obtained sensor data from the vendor who maintains the TxDOT Dallas sensor data. For California, the data were downloaded from the PeMS website by entering the highway, date, and milepost range desired. Each region bins its speed data with different time intervals. For California, data are recorded in hourly intervals, and Dallas sites are recorded in one-minute intervals. Because of the difference in time intervals, evaluations were conducted by city.

Previous research (*16*) demonstrated that natural light conditions affect speed; therefore, only daytime conditions were included in this analysis. The time the sun rose and set for each city for each day was identified. For all cities, dawn was defined as 30 minutes before and after sunrise, and dusk was defined as 30 minutes before and after sunset. Dawn, dusk, and night speed data were removed for this analysis. Depending on the month and day, dawn times ranged between 6 and 7 a.m., and dusk varied between 6 and 8 p.m.

Additional cleaning of the data included removing any data where the managed lane volume was zero and where the average speed on either the managed lane or the general-purpose lane exceeded 90 mph.

WEATHER

Because rain or fog could be a factor affecting speed of drivers, the weather present on each day represented in the database was identified. Websites with weather archives were searched in order to determine the amount of rainfall in a 24-hour period and if other weather events took place. A website called Weather Underground provided weather data according to day and time. Precipitation data were given for a 24-hour period, whereas weather events such as fog were given by the time of day. For most of the days in the dataset, no precipitation occurred. Table 29 shows the days when there was some precipitation recorded. In most cases, there was less than 0.19 inch of rain in a 24-hour period. Only one day had more than 0.19 inch—on July 18, 2015, in Los Angeles, there was 0.36 inches of rain. The research team selected a precipitation level of 0.1 inch in a 24-hour period as the limit for when the data for that day would be removed.

Table 29. Weather incidents.

State	City	Date	Precipitation (in)[a]
Days retained in dataset because precipitation was minimal (defined as being less than 0.09 inch in a 24-hour period)			
California	Los Angeles	3/18/2015	T[b]
California	Los Angeles	5/18/2015	T
Texas	Dallas	1/8/2014	0.09
Texas	Dallas	1/10/2014	0.08
Texas	Dallas	9/12/2014	0.04
Texas	Dallas	10/10/2014	0.05
Texas	Dallas	12/12/2014	0.01
Days removed from dataset because precipitation was more than 0.1 inch in a 24-hour period			
California	Los Angeles	12/17/2014	0.15
California	Orange County	12/17/2014	0.11
California	Los Angeles	7/18/2015	0.36
California	Orange County	7/18/2015	0.18
Texas	Dallas	5/14/2014	0.19

[a] Determined from www.wunderground.com, inches of rainfall in a 24-hour period.
[b] T = trace of precipitation.

OPERATIONAL ANALYSIS

Linear mixed-effects models were used to analyze the speed data. Table 30 provides descriptions of the variables considered in the statistical evaluations. Initial investigations indicated that the analyses should be done by congestion levels to provide a better opportunity to identify whether the managed lane geometrics affect the managed lane speed.

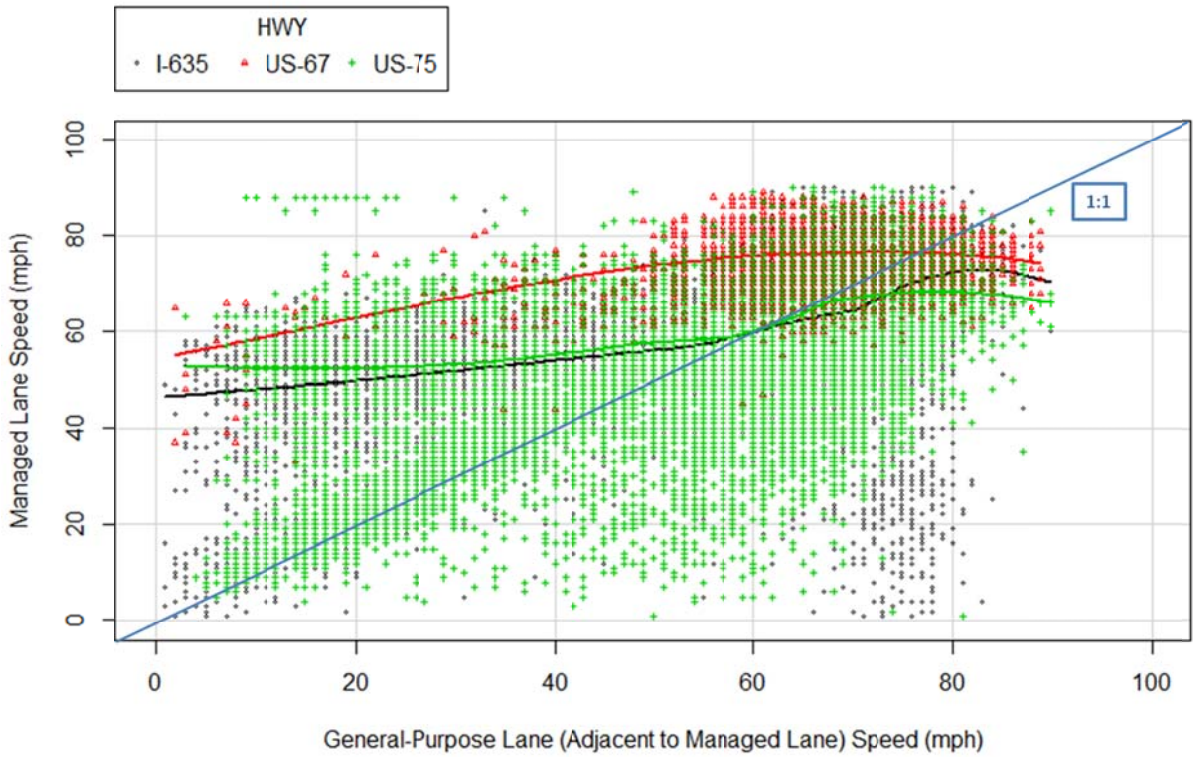
Table 30. Description of variables considered in statistical analyses.

Variable Name	Description
Buf_Type	Buffer type between managed lane and general-purpose freeway lanes—either pylons or flush
ENVELOPE	Sum of left shoulder width, managed lane width, and buffer width (ft)
GP_Adj_LW	General-purpose lanes, width of lane adjacent to the managed lane (ft)
GP_Avg_LW	General-purpose lanes, average lane width (ft)
GP_SPD	General-purpose, measured speed for the given increment of time (one hour in California, one minute in Dallas [mph])
GP_SW	General-purpose lanes, right shoulder width (ft)
GP_VOL	General-purpose volume (California represents average over all freeway lanes, while Dallas represents the adjacent lane volume that has been adjusted to one hour [vph])
HOV_BW	Buffer width (ft)
HOV_F_RGT	Managed lane, feature to the right, either flush buffer (buf) or flush buffer with pylons (buf + pyl)
HOV_LW	Managed lane, lane width (ft)
HOV_SW	Managed lane, left shoulder width (ft)
HOV_VOL	Managed lane, volume (Dallas data were in one-minute increments [veh/min] and California data were in one-hour increments [vph])
HOV_VOLrate	Managed lane, adjusted one-hour volume (Dallas counts were adjusted to reflect a one-hour period, California data were already in one-hour increments [vph])
NUM_GP	General-purpose lanes, number of general-purpose lanes that are not barrier-separated and are moving in same direction
PSL	Posted speed limit (mph)
WKD	Weekday (Monday, Tuesday, Wednesday, Thursday, or Friday)

Dallas, Texas

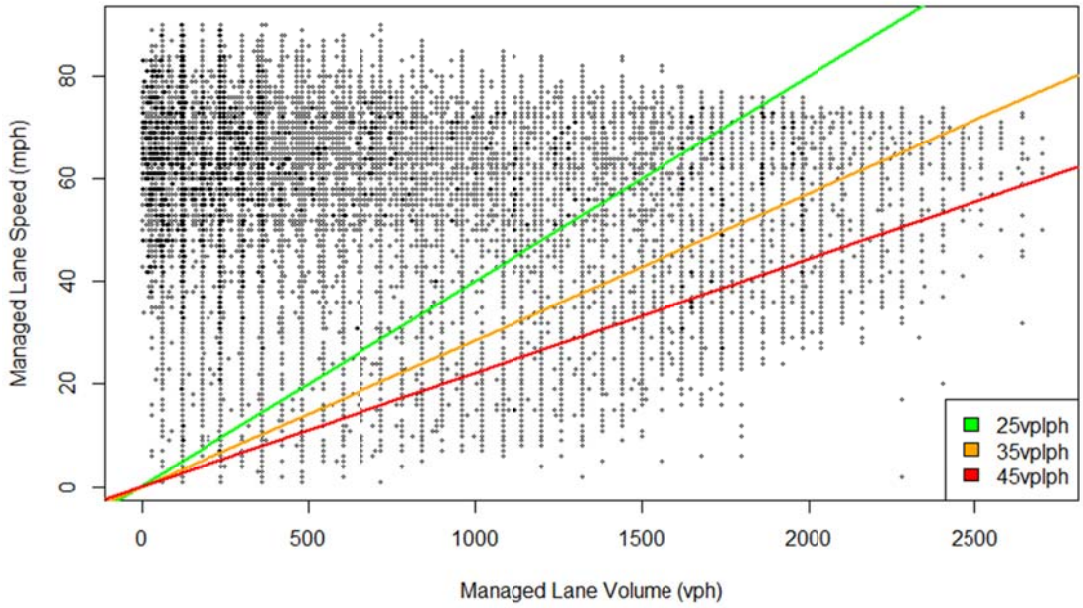
The plot of the speed data for the Dallas freeways is shown in Figure 33. As illustrated in the graph, there were several readings where the daytime speed in the neighboring general-purpose lane was higher than the speed in the managed lane; however, this plot may not provide a true appreciation of the number of data points within the dataset. Overall, the recorded speeds in the managed lane were higher than the recorded speed in the adjacent general-purpose lane except when the general-purpose lane was operating near or above the posted speed limit.

Figure 34 shows the plot of the managed lane speed data by the managed lane volume, while Figure 35 shows a similar plot for the general-purpose lane that is next to the managed lane. The managed lane volume shown in Figure 34 is the hourly volume rate as converted from the one-minute counts. The plots of volume to speed for the Dallas data do not show as clear of a speed-volume relationship as can be seen in the California data (discussed in the next section).



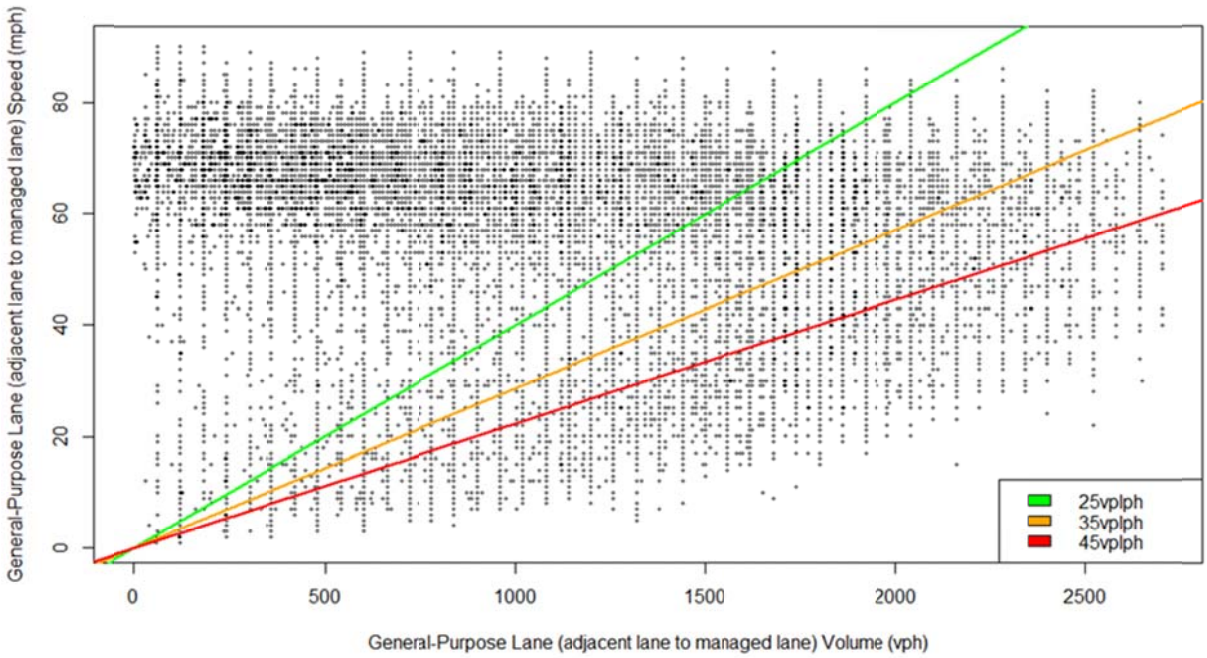
Source: TTI

Figure 33. Dallas plot of managed lane versus adjacent general-purpose lane speeds.



Source: TTI

Figure 34. Dallas plot of managed lane speed by managed lane hourly volume (calculated from one-minute counts).



Source: TTI

Figure 35. Dallas plot of general-purpose lane speed by general-purpose lane hourly volume (calculated from one-minute counts).

Analysis—Uncongested Managed Lane

The initial analysis with the Dallas data focused on when the managed lane was uncongested (defined as having density less than 25 vphpl and speeds greater than 45 mph). This analysis compared the speeds on uncongested managed lanes with no restrictions on the speeds or density within the general-purpose lanes. To represent the geometry of the facility, the entire managed lane envelope dimension resulted in a model that had better model fit measures. For Dallas, the minimum managed lane envelope width (i.e., left shoulder width, lane width, and buffer width) was about 16 ft; therefore, the managed lane envelope variable included a 16-ft offset. This result in the variable's coefficient representing the increase in speed was associated with an increase in the size of the envelope beyond the minimum value.

Also considered was how best to handle the presence of pylons. Based upon several modeling attempts, the best method to handle the effect of pylons was to create a new variable that accounted for both the presence of the pylons and the effects of the general-purpose vehicle speed. Separate coefficients were identified for the flush buffer and for the flush buffer with pylons that reflected a change in the managed lane speed per unit increase in the general-purpose lane speed. The best model that included only statistically significant variables (with one exception, the variable for flush buffers) is shown in Table 31 with the range of the variables being considered provided in Table 32. The variable to reflect the flush buffer (i.e., no pylons) was kept in the model for comparison with the variable that reflected the pylons in the buffer.

Speeds on managed lane during daytime uncongested conditions are high, as illustrated with the intercept being 51.9 mph. The 51.9-mph speed value will decrease or increase depending on the conditions present. The variable that contributes the most to influencing the predicted speed on the managed lane is the managed lane geometry. Speeds are 3.2 mph faster for each 1-ft increase in managed lane geometry width beyond 16 ft. The speeds in the general-purpose lanes influence the uncongested managed lane speeds when pylons are present, but perhaps by less than anticipated. An increase in general-purpose lane speed of 10 mph is associated with only about a 0.9-mph increase in managed lane speeds.

Table 31. Dallas linear mixed-effects model results when the managed lane is uncongested.

Variable	Value	Std.Error	DF	t-value	p-value
(Intercept)	51.91219	2.801838	150980	18.52791	0
HOV_VOLrate^2 / 100,000	−0.01931	0.006907	150980	−2.7966	0.0052
HOV_VOLrate	−0.0011	9.96E-05	150980	−11.0774	0
ENVELOPE - 16	3.22346	1.162922	20	2.77186	0.0118
WKDWednesday	−0.37716	0.149765	151	−2.51834	0.0128
GP_SPD:HOV_F_RGTbuf	0.00712	0.005256	150980	1.35562	0.1752
GP_SPD:HOV_F_RGTbuf + pyl	0.09449	0.001831	150980	51.60253	0

Note: Conditions represented:

- Managed lane speed >45 mph.
- Managed lane density <25 vphpl.

See Table 30 for descriptions of variables.

Table 32. Dallas range of values for variables included in Table 31.

Variable	Mean	Std.Dev	Min	Max	N
HOV_BW	4.298658	0.748258	3	5.65	154881
HOV_LW	11.13212	0.446475	10.2	11.9	154881
HOV_SW	2.892921	2.053338	1.22	7.4	154881
ENVELOPE	18.3237	1.468789	16.7	21.5	154881
HOV_SPD	65.11712	8.668927	45	90	154881
HOV_VOL	5.386264	5.63003	1	44	154881
HOV_VOLrate	361.1136	347.676	0.197911	1860	154881
HOV_DEN	5.638468	5.515449	0	25	154881
GP_SPD	63.34137	11.3116	1	90	154881
GP_VOL	17.94724	8.635084	1	45	154881
GP_VOLrate	1217.021	514.5031	0.243161	2700	154881
GP_DEN	20.98016	12.74891	0	180	154881

Analysis—Uncongested Managed Lane and Congested General-Purpose Lanes

The influence of the general-purpose lanes may be even greater when the general-purpose lanes are congested. Congested conditions were defined in this study as having density greater than 25 vphpl. The geometry of the facility was represented with the managed lane envelope dimension with a 16-ft offset. The method used to account for the influence of pylons and general-purpose lane speeds remained the same as discussed in the previous section—the variable was combined with the general-purpose speed variable. The best model that included

only statistically significant variables is shown in Table 33 with the range of values for those variables shown in Table 34.

The intercept for this model is 50.2 mph, again demonstrating that daytime speeds on uncongested managed lanes, even when the general-purpose lanes were congested, were high. Similar to when the general-purpose lanes were uncongested, the variable that contributed the most to influencing the speed on the managed lane was geometry—for this condition, the width of the managed lane envelope. Speeds were about 3.1 mph faster for each 1-ft increase in managed lane envelope width beyond 16 ft. The speeds in the congested general-purpose lanes influence the uncongested managed lane speeds (statistically significant). When pylons are present, the increase in managed lane speed for an increase in general-purpose lane speed is greater. A 1.0-mph increase in general-purpose lane speed is associated with a 0.12-mph increase in managed lane speed when pylons are present and only 0.03-mph increase when pylons are not present.

Table 33. Dallas linear mixed-effects model results when the managed lane is uncongested and general-purpose lanes are congested.

Variable	Value	Std.Error	DF	t-value	p-value
(Intercept)	50.24775	2.689439	39780	18.68336	0
HOV_VOLrate^2 / 100,000	−0.02275	0.012077	39780	−1.88354	0.0596
HOV_VOLrate	−0.00079	0.000178	39780	−4.43082	0
ENVELOPE - 16	3.11776	1.118739	20	2.78686	0.0114
WKDWednesday	−0.57982	0.16483	143	−3.51771	0.0006
GP_SPD:HOV_F_RGTbuf	0.03141	0.011125	39780	2.82356	0.0048
GP_SPD:HOV_F_RGTbuf + pyl	0.11787	0.002537	39780	46.46636	0

Note: Conditions represented:

- Managed lane speed >45 mph.
- Managed lane density <25 vphpl.
- General-purpose lane density >25 vphpl.

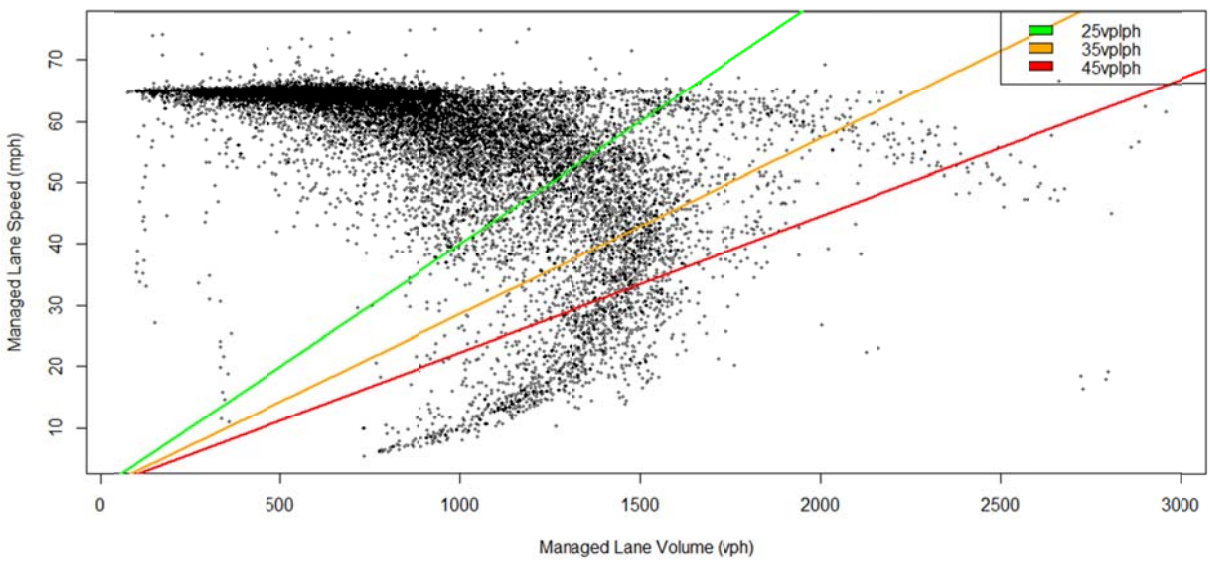
See Table 30 for descriptions of variables.

Table 34. Dallas range of values for variables included in Table 31.

Variable	Mean	Std.Dev	Min	Max	N
HOV_BW	4.318685	0.69248	3	5.65	42273
HOV_LW	11.16914	0.458734	10.2	11.9	42273
HOV_SW	2.655522	1.902653	1.22	7.4	42273
ENVELOPE	18.14335	1.398458	16.7	21.5	42273
HOV_SPD	62.10233	8.654539	45	89	42273
HOV_VOL	7.515554	5.882629	1	30	42273
HOV_VOLrate	514.5241	373.9791	29.75207	1800	42273
HOV_DEN	8.477193	6.338872	0.43	25	42273
GP_SPD	53.10688	14.87332	6	86	42273
GP_VOL	26.37901	7.390232	4	45	42273
GP_VOLrate	1797.337	320.8052	505.7851	2700	42273
GP_DEN	36.73787	12.37656	25.01	180	42273

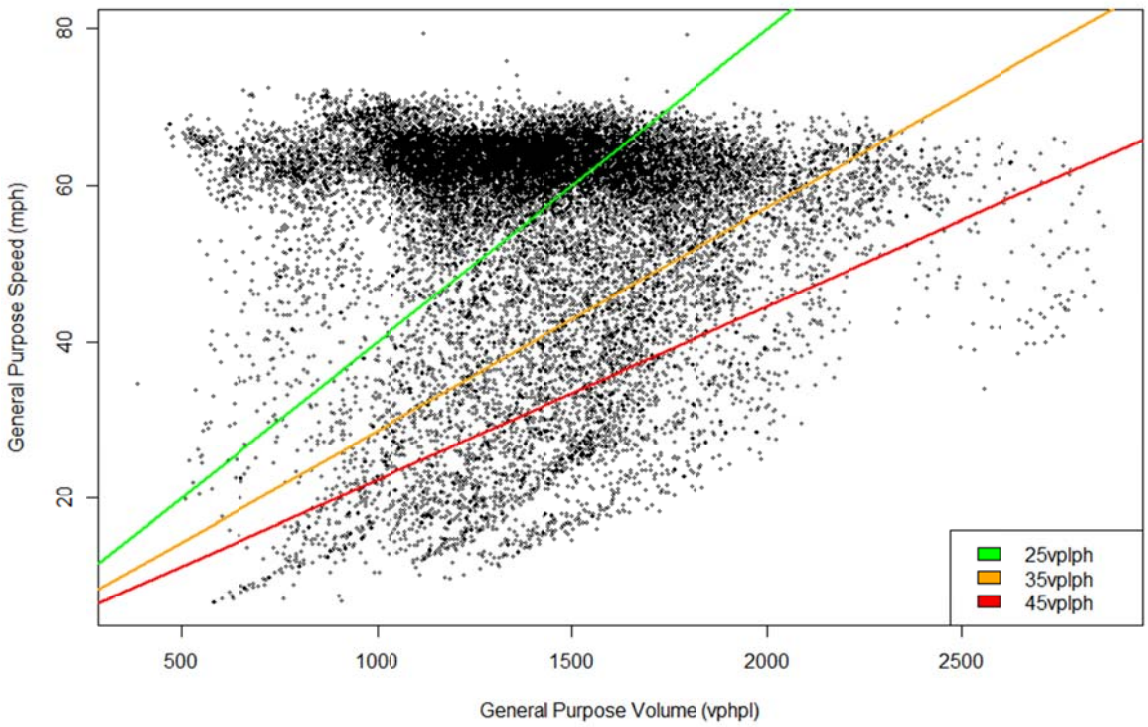
Los Angeles and Orange County, California

Figure 36 shows the managed lane speed data by volume for all sites in California. The density ranges shown in vehicles per lane per hour are also superimposed on the graph. The speed-volume relationship shows the expected backward "C" pattern. Figure 37 provides a similar plot for the general-purpose lanes. The freeway volume was converted to a per-lane volume. The general-purpose speed-volume plot (see Figure 37) shows more variability than the managed lane plot (see Figure 36). For example, on general-purpose lanes, a 30-mph operating speed is associated with per-lane volumes between 750 and 2000 vph. For the managed lane, a 30-mph speed measurement was generally only seen when the volume per lane was between 1200 and 1700 vph. Figure 38 shows a comparison of the managed lane speed by the speed on the general-purpose lanes. As compared to Texas data (see Figure 33), Figure 38 shows less variability in managed lane speed for a given general-purpose lane speed. The measurement increment (one hour for California, one minute for Texas) probably contributed to the greater variability shown in the Texas data.



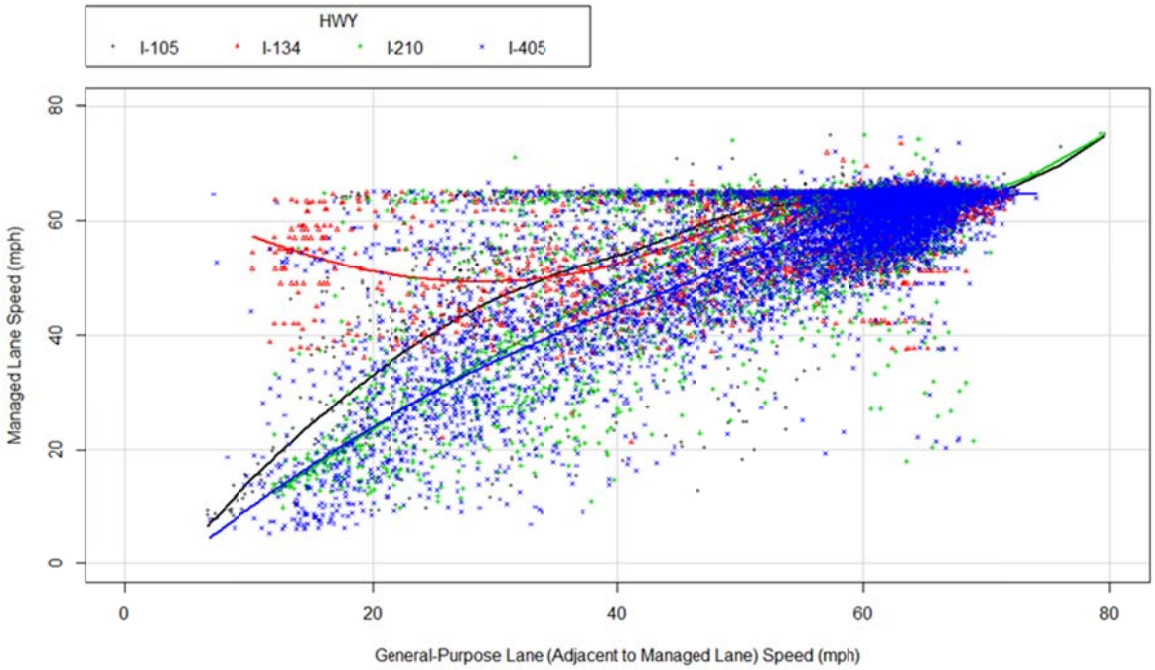
Source: TTI

Figure 36. California plot of managed lane speed by managed lane volume.



Source: TTI

Figure 37. California plot of general-purpose lane speed by general-purpose per-lane volume.



Source: TTI

Figure 38. California plot of managed lane speed by general-purpose lane speed.

Analysis—Uncongested Managed Lane

The initial analysis focused on when the managed lanes were not congested (defined as having density less than 25 vphpl). Another filter used was to only include managed lane speeds greater than 45 mph since the plot shown in Figure 36 revealed some potential outliers when volume was less than 500 vph. The preliminary findings indicated that the effects of the managed lane dimensions were not significant, whether they were considered grouped into a single managed lane envelope variable or uniquely as left shoulder width, managed lane width, or buffer width. Table 35 shows the results where only significant variables are included. Table 36 provides the range of values for the variables considered in this evaluation of uncongested manage lanes. Even with a large range of buffer widths (1 to 13 ft) and left shoulder widths (1 to 20 ft), these geometric variables were not significant.

The speed of a managed lane vehicle during uncongested periods is high, as indicated with an intercept of 52.7 mph. The significant variables for the uncongested managed lane scenario were the volume on the managed lane, the speed on the general-purpose lanes, and certain days of the week. According to the model coefficients, the managed lane speed increases by about 0.24 mph for each 1.0-mph increase in the general-purpose speed. For this dataset, drivers on the managed lane were driving 0.4 mph faster on Monday and Friday as compared to other weekdays.

Table 35. California linear mixed-effects model results when the managed lane is uncongested.

Variable	Value	Std.Error	DF	t-value	p-value
(Intercept)	52.72376	0.418218	13956	126.0676	0.00000
HOV_VOL^2 / 100,000	−0.26012	0.027939	13956	−9.31019	0.00000
HOV_VOL	−0.00389	0.000479	13956	−8.12387	0.00000
GP_SPD	0.23797	0.003333	13956	71.40422	0.00000
WKD = Monday or Friday	0.39622	0.107347	622	3.69104	0.00020

Note: Conditions represented:

- Managed lane density <25 vphpl.
- Managed lane speed >45 mph.

See Table 30 for descriptions of variables.

Table 36. California range of values for variables included in Table 35.

Variable	Mean	Std.Dev	Min	Max	N
HOV_SPD	62.19568	4.119164	45	75	15755
HOV_VOL	737.0611	295.1485	78	1620	15755
HOV_BW	2.944399	2.226236	1	13	15755
HOV_LW	11.02412	0.534088	10	12	15755
HOV_SW	4.494954	4.901488	1	20	15755
GP_SPD	60.42793	8.204966	7.4	79.5	15755
GP_VOL	6125.786	1430.274	1845	14121	15755

Analysis—Uncongested Managed Lane and Congested General-Purpose Lanes

The next analysis considered whether the relationships between managed lane operating speed and the potential influential variables are similar when the operations in the general-purpose

lanes are congested and the operations in the managed lane are uncongested. Again, the managed lane geometric variables (left shoulder width, lane width, and buffer width) were not significant. Table 37 provides the results when only significant variables are included. Table 38 lists the range of values for the variables. The significant variables were managed lane volume and general-purpose speed and volume per lane. As volume increases, in either the managed lane or the general-purpose lane, managed lane speed decreases. As the speed increases in the general-purpose lane, the speed increases in the managed lane. The base speed of the manage lane for this condition was 57.5 mph, again reflecting the very high speeds in the managed lane.

Table 37. California linear mixed-effects model results when the managed lane is uncongested and the general-purpose lanes are congested.

Variable	Value	Std.Error	DF	t-value	p-value
(Intercept)	57.5262	0.68921	4107	83.4669	0
HOV_VOL	−0.00903	0.000268	4107	−33.7443	0
GP_SPD	0.2036	0.006554	4107	31.06622	0
GP_VOL/NUM_GP	−0.00071	0.000369	4107	−1.93367	0.0532

Note: Conditions represented:

- Managed lane density >25 vphpl.
- Managed lane volume >500 vph.

See Table 30 for descriptions of variables.

Table 38. California range of values for variables included in Table 37.

Variable	Mean	Std.Dev	Min	Max	N
HOV_SPD	60.13826	5.236264	45	74.9	5408
HOV_VOL	851.6265	270.4375	110	1612	5408
HOV_BW	2.779956	1.987112	1	13	5408
HOV_LW	10.98285	0.521517	10	12	5408
HOV_SW	4.364183	4.793758	1	20	5408
GP_SPD	55.06244	10.97162	7.4	70.5	5408
GP_VOL	7081.16	1319.032	2408	14121	5408

Analysis—Congested Managed Lane

For the California data, an analysis was conducted for when the managed lane was congested (i.e., data below the 25 vphpl curve in Figure 36) with several models being considered. Buffer width was nearly significant in one of the models (see Table 39 and Table 40) with a p-value of 0.108. This result provides an indication that the width of the buffer may be lessening the impact of changing general-purpose lane operations on the managed lane operations.

Variables that were statistically significant included the volume in the managed lane, the general-purpose speed, the volume in the general-purpose lanes, and the day of the week. For day of the week, speeds are higher on Monday, Tuesday, Wednesday, and Thursday compared to Friday. The most influential variables on a congested managed lane speed are the managed lane volume and the speed in the general-purpose lane.

Table 39. California linear mixed-effects model results when the managed lane is congested.

Variable	Value	Std.Error	DF	t-value	p-value
(Intercept)	−11.1073	2.676548	4419	−4.14984	0
HOV_VOL^2 / 100,000	−0.45112	0.079935	4419	−5.64366	0
HOV_VOL	0.024375	0.002813	4419	8.66599	0
HOV_BW	0.474455	0.292387	95	1.6227	0.108
GP_SPD	0.481931	0.008807	4419	54.72193	0
GP_VOL/NUM_GP	0.003373	0.000627	4419	5.38319	0
WKDMonday	3.452589	0.855434	331	4.03607	0.0001
WKDThursday	1.117076	0.565823	331	1.97425	0.0492
WKDTuesday	3.686526	0.850216	331	4.33599	0
WKDWednesday	2.829166	0.485951	331	5.82191	0

Note: Conditions represented:

- Managed lane density >25 vphpl.

See Table 30 for descriptions of variables.

Table 40. California range of values for variables included in Table 39.

Variable	Mean	Std.Dev	Min	Max	N
HOV_SPD	46.93815	15.53697	5.4	69.2	5625
HOV_VOL	1615.262	339.8781	729	2958	5625
HOV_BW	2.616267	1.552195	1	13	5625
HOV_LW	10.932	0.494433	10	12	5625
HOV_SW	3.919644	4.199763	1	20	5625
GP_SPD	45.19909	16.70304	6.6	70.4	5625
GP_VOL	6291.337	1690.257	2032	13945	5625

CHAPTER 5

ACCESS

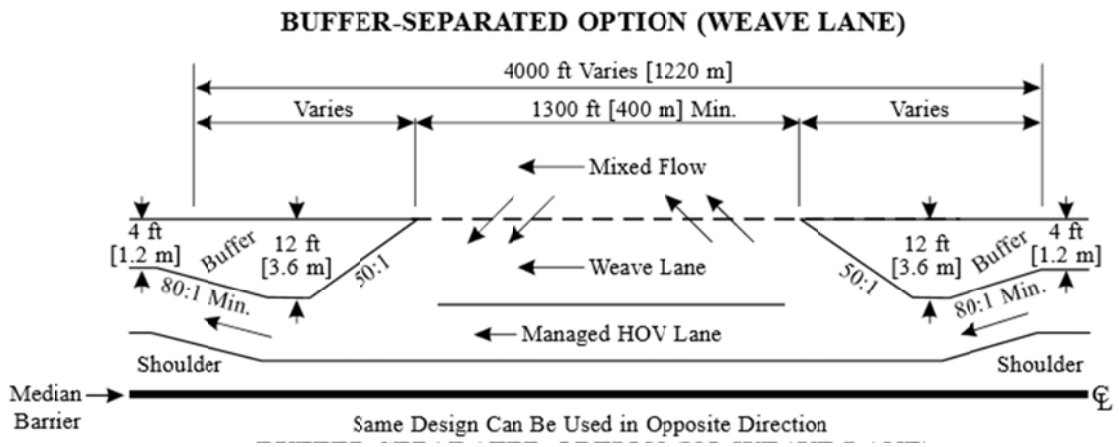
INTRODUCTION

Research Problem Statement

The 2004 AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*) includes a trade-off analysis on various design options for reducing width from recommended dimensions. This guide provides suggested priorities of cross-section adjustments to be made to a facility's design. In the time since its publication, additional operational strategies for managed lanes have emerged, including the use of pricing to meter traffic, dynamic shoulder lanes, active lane control signals coupled with variable speed limits, and additional examples of reduced lane widths and access treatments on new managed lane facilities.

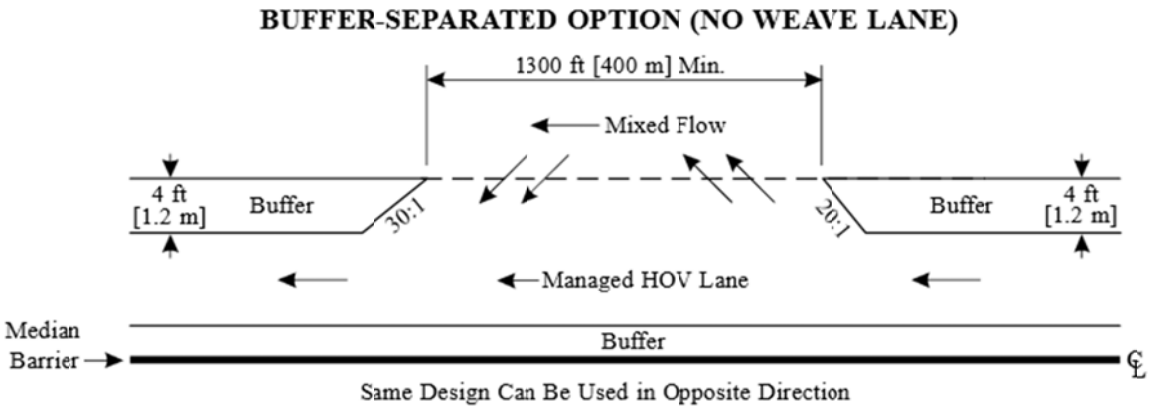
A survey of practitioners in Phase I of this project (see Appendix C) identified access-related issues as one of the largest design gaps. In particular, guidance on how to evaluate, design, and implement a wide variety of at-grade access treatments is lacking in current guidance treatises. A much clearer understanding and appreciation for best practices associated with access in its different forms is important to properly accommodate the anticipated volumes of entering and exiting traffic. Access guidance and analysis requirements were developed by Caltrans in a policy memorandum in 2011 (*2*) based on safety studies undertaken in California and Texas, but further clarity is needed to assess the roles that access plays in performance, impacts to general-purpose traffic, demand, revenue, and enforcement. For example, at-grade access guidance is lacking for higher-volume dual-lane treatments when compared to a much larger number of single-lane facilities. Direct-access features also represent guidance needs since some designs have experienced extraordinary crash events that have engaged practitioners in peer reviews of potential treatments to mitigate specific points of driver confusion. An ever larger number of projects seem to be experiencing different issues regarding access, and a number of projects have altered their access plans after opening to conform to changing operational conditions, enforcement issues, and driver confusion. Access equity is also an issue emerging in some locales, since the long distances between access locations may preclude access to adjoining and impacted municipalities along a project.

The variety of access treatments also suggest that definitions and examples are needed to ensure that practitioners understand the options available. Weave zones, weave lanes, separate versus shared ingress/egress movements, and restricted (or limited) and open access are all possible configurations, examples of which are shown in Figure 39 through Figure 42. Dimensions shown in these examples are inherent to their respective sources and are provided here merely for illustration.



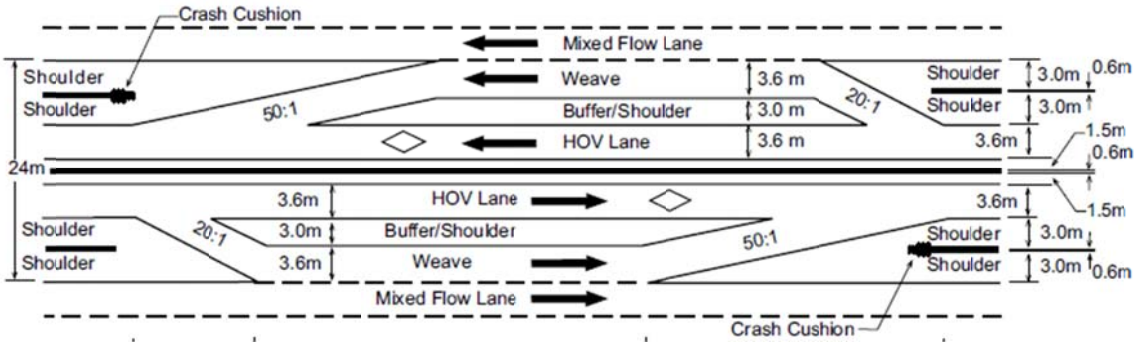
Source: (*31*)

Figure 39. Example weave lane for a shared ingress/egress point on a restricted-access facility.



Source: (*31*)

Figure 40. Example weave zone for a shared ingress/egress point on a restricted-access facility.



Source: (*29*)

This figure is solely intended for use in the California Department of Transportation's ("Caltrans") High-Occupancy Vehicle Guidelines as an example of High-Occupancy Vehicle lanes used within California. It is neither intended as, nor does it establish, a legal standard for use in other environments. The figure is for the information and guidance of the officers and employees of Caltrans. This figure is not a substitute for engineering knowledge, experience or judgment. The examples given herein are subject to amendment as conditions and experience may warrant. Copyright 2003 California Department of Transportation, all rights reserved.

Figure 41. Example weave lanes for separate ingress/egress points on a restricted-access facility.

Source: Google Earth

Figure 42. Example open-access facility.

This study effort, referred to as Study 5R.4, gathered information related to existing guidance and practices pertaining to the design of access to managed lane facilities. Based on the information obtained, the study also considered potential future research needs and identified opportunities for changes to the guidelines document developed in Phase I of the research.

Objective

The objective of this study—Study 5R.4—was to answer the following questions and topics for practitioners to evaluate access as part of planning, design, and implementation activities.

- What are appropriate ways to evaluate and consider impacts of restricted and continuous at-grade access?
- What level of operational analysis is needed during the planning phase to determine operational feasibility?
- What are appropriate criteria for determining ingress/egress locations and impacts on pricing demand?
- What are preferred approaches to at-grade access for different levels of demand associated with single- and multilane concurrent-flow treatments?

Research Methodology

The research approach was divided into three main activities:

- **Survey of recent practice by practitioners**—A telephone/email questionnaire was developed to ask specific access-related questions to practitioners to gain insight on how they make decisions on access and what guidance they used or would like to have. This task used information from the interviews conducted as part of Study 5R.1 to develop specific follow-up questions for selected interview participants and other practitioners involved in access decisions for a variety of managed lane facilities in the United States.
- **Compilation of existing policies**—Researchers reviewed the sources documented in the literature, manuals, and guidance resources to summarize the available guidance and supporting information on this topic. Researchers also identified additional resources through a literature search and through suggestions from panel members and practitioners.
- **Findings and conclusions**—Finally, researchers processed the information obtained from the first two tasks to identify common design decisions related to access, potential developing trends, useful revisions to the draft guidelines document, and suggestions for future research needs.

SURVEY OF PRACTICE

An email and telephone survey of selected managed lane practitioners was conducted in order to identify existing practices and decision-making procedures as they pertain to the design of managed lane access. The intent of the survey was to follow up on the interviews conducted in Study 5R.1, with a focus on access characteristics and the decisions associated with them, to answer the questions described in the study objective.

Methodology

The primary source of information was drawn from practitioners who had close knowledge of or were instrumental in the decision-making process for the design or implementation of access to managed lanes. Participating practitioners served in various disciplines as they pertain to design decisions, and some worked for public agencies while others were employed in the private sector. Furthermore, some practitioners were not involved in the initial design of the managed lane facilities being discussed, but they had been actively engaged in recent access designs or redesigns and had insights into how those decisions were made. Eight practitioners were invited to participate, representing experience with access on the following 10 managed lane facilities:

- Atlanta, Georgia:
    - I-75 South Managed Lanes.
    - I-75/575 North Managed Lanes.
    - I-85 Managed Lanes.
- Bay Area of California:
    - I-680 Express Lanes.
    - SR 237/I-880 Express Lanes.

- Houston, Texas:
    - I-10 Katy Managed Lanes.
- Los Angeles, California:
    - I-110 Managed Lanes.
- Salt Lake City, Utah:
    - I-15 Managed Lanes.
- Seattle, Washington:
    - I-405 Phase I Managed Lanes.
    - SR 167 Managed Lanes.

Researchers developed a list of 11 questions related to access, subdivided into three categories. The full list of questions was as follows:

- Location of access on limited-access facilities:
    - What is the variation in distances between access points on your facility(ies)?
    - What factor(s) led to the decision(s) to provide this access (e.g., operations, demand, space or ROW, safety, agency policy, etc.)?
    - What is the typical weave distance between ML access and GP access (e.g., XX ft per lane change)?
    - Do you periodically review (or have you reviewed) the existing access points to determine whether they meet their intended purpose or whether changes could be made?
    - Based on the location, design, and performance of the existing access points, what are some tools/guidelines/information sources you did not have in the original design that would have been beneficial?
- Comparison/conversion of limited access to continuous access:
    - What factor(s) led to the decision to provide continuous access on some of your project(s) (e.g., operations, safety, policy, etc.)?
    - What are appropriate ways to evaluate and consider effects of restricted versus continuous at-grade access (e.g., what measures of effectiveness does/will your agency use or prefer to use)?
    - What are some tools, guidelines, or information sources you did not have during the conversion process that would have been beneficial?
- Comparison of shared ingress/egress weave zone and unidirectional (separate ingress and egress ramps) access:
    - Are there differences in preferred at-grade access for single-lane versus multilane treatments?
    - Does the preferred access treatment change at a particular volume or level of demand?
    - What are some tools/guidelines/information sources you did not have that would have been beneficial?

Researchers contacted practitioners and distributed the questionnaire in the summer of 2015. Practitioners were identified through the participants list from Study 5R.1 and additional contacts known to the research team. Researchers initially contacted practitioners by telephone to invite them to participate and then followed up by email to provide the list of questions and schedule a time for follow up if necessary. Practitioners were given the option

of returning the completed questionnaire by email or scheduling a telephone call with a researcher to answer the questions verbally. Invitations for the survey were submitted by email only to the participants identified through the process described above, and completion of the survey was limited to only those invited by email. In total, 10 questionnaires were distributed and eight were returned; seven responses were completed by email and one by telephone. Responses provided information about nine existing managed lane facilities, including two that have planned changes to their access.

No practitioner was asked all 11 questions because not all questions applied to any single facility, and some of the questions were addressed in Study 5R.1. Rather, questions were intentionally selected to apply to characteristics of each corridor. The questions assigned to each corridor are summarized in Table 41.

Table 41. Questions asked for each managed lane corridor in the practitioner survey.

	Location of Access					**Limited/Continuous**			**Shared/Unidirectional**		
Facility	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**1**	**2**	**3**
Atlanta I-75S	X	X	X		X						
Atlanta I-75/575N	X	X	X		X						
Atlanta I-85S	X		X	X	X				X	X	X
Bay Area I-680 SB (Existing)	X	X	X	X	X				X	X	X
Bay Area SR 237/I-880 (Existing)	X	X	X	X	X				X	X	X
Bay Area I-680 NB & SB (Planned)		X			X	X		X			
Bay Area SR 237/I-880 (Planned)		X			X	X		X			
Houston I-10	X	X	X	X	X				X	X	X
Los Angeles I-110	X		X	X	X						
Salt Lake City I-15	X	X	X	X	X	X	X	X			
Seattle I-405	X	X	X						X	X	X
Seattle SR 167				X	X	X	X	X			

Survey Results

This section summarizes the responses received from the questionnaire.

Location of Access

Question 1: What is the variation in distances between access points on your facility(ies)?

Practitioners gave a wide range of distances in response to this question. The extent of those ranges was just less than 1 mi to about 7.4 mi, but in general, spacing of access was typically between 1 and 3 mi for all the facilities studied.

Question 2: What factor(s) led to the decision(s) to provide this access? (e.g., operations, demand, space or ROW, safety, agency policy, etc.)

There was a wide variety of factors provided in the responses to this question. Location and type of access may be a result of a regional policy, an operational analysis, a safety consideration, constraints due to available right of way or adjacent interchanges, or other factors. In particular, weaving and other operational effects were commonly listed as important factors.

For each corridor, more than one factor was described as having an effect on the decision-making process. In each case, the facility operator had to select one or more of these factors as having priority over other potential factors. Below is a summary of the answers provided for the facilities in question.

- Operational analyses identified important characteristics and controlling factors, both for the number of access points and their optimal locations (e.g., maximizing the length of managed lane segments to minimize the potential traffic conflicts at the weave zones and allowing for the greatest time savings).
    - Weaving analysis (six facilities).
    - Travel time or other corridor operational analysis (three facilities).
    - Origin/destination analysis (three facilities).
    - Bottleneck identification (two facilities).
- Access meets or exceeds AASHTO standards regarding minimum ramp terminal spacing, geometry, and construction (three facilities).
- Use of existing HOV lane infrastructure (three facilities).
- A formal crash analysis or other consideration of safety (three facilities).
- Regional Managed Lane System Plan recommended access point locations, facility type, and access type on a regional basis for the managed lane program (e.g., direct access to managed lanes is separated from general-purpose interchanges, which also affects location and spacing of managed lane access; two facilities).
- Access meets or exceeds *Highway Capacity Manual* (*26*) standards.
- Specific guidelines or reports referenced for recommended weaving distances.
    - Caltrans (*2*, *5*) (two facilities).
    - WSDOT (*29*).
    - Texas A&M Transportation Institute (*30*).
    - University of Texas—Arlington (*31*).
- Revenue study/analysis of capacity available for sale to HOT users (two facilities).

- Network connectivity and the ability to easily travel from one freeway to another were considered (two facilities).
- Availability of sufficient right of way (two facilities).
- Access to transit stations and major employment centers.
- At least one access to/from each local jurisdiction along the facility.
- Slip ramps on a reversible facility are directional based on the time of day the facility operates in each direction.
- Provision of appropriate lighting.
- Prioritization of driver expectancy.

Question 3: What is the typical weave distance between ML access and GP access (e.g., XX ft per lane change)?

Typical weaving distances were expressed in units of the number of feet per lane change. The most common distances were between 600 and 1200 ft, consistent with recent research recommendations and some states' guidelines, though one facility used 500 ft per lane change. Two facilities had more than a mile per lane change for their largest distance because the beginning or end of the managed lane facility was that far from the nearest general-purpose access, but other distances were consistent with the 600–1200 ft range.

Question 4: Do you periodically review (or have you reviewed) the existing access points to determine whether they meet their intended purpose or whether changes could be made?

Of the five facilities for which this question was asked, four of them have had at least one review of their access points. Two corridors were reviewed by the agencies operating the facility as part of a routine review or a request from political leaders, while the other two reviews were largely in response to driver feedback.

In response to one agency-led review, an access point was added to improve entry into the facility and flexible delineators were added near one access point to discourage illegal weaving. In the other agency-led review, the facility was retrofitted to provide access centered over the general-purpose interchanges to allow for consistency and facilitate driver expectation.

For the two reviews motivated by driver feedback, one facility will be converted from limited access to continuous access as painted buffers are removed, while at the other facility, the length of selected access points was increased to improve drivers' ability to enter and exit the facility at preferred locations. The facility in which no review was conducted was converted from HOV operation to HOT operation as part of a demonstration project, and major changes to existing infrastructure were not allowed; however, specific access points are typically reviewed if an issue arises or complaint is made.

Question 5: Based on the location, design, and performance of the existing access points, what are some tools/guidelines/information sources you did not have in the original design that would have been beneficial?

The purpose of this question was to determine if there were key pieces of information that the practitioners would have used if they had been available at the time, or if there were new tools or guidelines that they developed as a result of their experiences. The research team believed that if these tools would be beneficial for the practitioners in this study, they would also have broader appeal for wide use within the profession on other current and future managed lane facilities.

Responses to the question from practitioners are summarized as follows:

- National guidance would be beneficial on weave distance per lane based on level of congestion (three corridors).
- Congestion-based guidelines for length of the at-grade weaving area would be helpful.
- Previous policy was that all express lanes must have double solid-line buffers in order to operate, but the region's policy has changed to operate express lanes similar to HOV lanes operated for over two decades without buffer or access restrictions. Restricted-access buffers will only be used in specific locations where they are needed for safety or operational reasons. Most area users prefer open access.
- An added step on one project was the necessity to coordinate with the DOT to provide the frequency and level of access it thought was necessary. This involved providing sufficient output from the corridor operational analysis to properly inform the DOT what could be expected for a given corridor configuration. A lesson learned was that it is important to ensure that each party has the same, and realistic, expectations of what is achievable within the modeling process. It may be necessary to manage expectations so that the agency is not planning to have more detail or information than it will actually receive, and so that large amounts of project resources are not expended to satisfactorily validate operational models.
- Better understanding of real-world examples of friction impacts from a virtual buffer would be useful. A facility with a virtual buffer was described as one in which the HOT lane has added width to accommodate higher performance (e.g., volume, speed, capacity) without restricting access. The respondent was unsure how a virtual buffer performed compared to a typical buffer in terms of friction between the traffic in the HOT lane and traffic in the adjacent general-purpose lane.
- It would have been beneficial if the original project scope allowed for a redesign of the ingress/egress locations using the latest HOV guidelines from the DOT for opening length and weaving distance per lane.
- One respondent said that understanding driver expectations of the access points would be helpful. This respondent was an early adopter of managed lane systems and did not have the ability to incorporate many lessons learned from other agencies.

Comparison/Conversion of Limited Access to Continuous Access

Question 1: What factor(s) led to the decision to provide continuous access on some of your project(s)? (e.g., operations, safety, policy, etc.)

The three practitioners who answered this question spoke of practical limitations on analysis, operational effects, and safety benefits. For facilities in one region, the previous process

assumed a buffer-separated facility with limited access and then an analysis was conducted to determine where access would be most beneficial. The length of the corridor made such an analysis very difficult because of competing demands and geometric limitations. Ultimately, the baseline assumption was changed to a continuous-access facility in which an analysis could identify locations where access should be restricted, and one facility opened with no restrictions. A similar arrangement was developed on another facility in which drivers complained about the lack of access; after considering operational and safety effects, the agency determined it could provide the unlimited access its road users desired without negatively affecting safety.

Question 2: What are appropriate ways to evaluate and consider effects of restricted versus continuous at-grade access (e.g., what measures of effectiveness does/will your agency use or prefer to use)?

One respondent indicated that safety, gap acceptance behavior, and revenue were all measures to consider, based on the hypothesis that by providing easier access, more drivers will take advantage of the lanes. The other respondent to this question focused on operational characteristics, specifically the traffic density in the managed lane and adjacent general-purpose lanes.

Question 3: What are some tools, guidelines, or information sources you did not have during the conversion process that would have been beneficial?

The three respondents to this question indicated a desire to be able to learn from the lessons from previous installations. One respondent gave some specific suggestions as follows:

- Little research is available on the best way to configure access openings (ingress, egress, or both) in terms of length and striping patterns for buffer-separated facilities. Project teams have developed approaches that they believe function appropriately, but the practitioner stated that there is insufficient data to prove it. For example, how well do weaving areas really work?
- The practitioner stated that it would be good for the MUTCD to have a signing scheme for continuous-access facilities that is based on driver decision-making. (*Research team's note: there is a signing scheme in the MUTCD for continuous-access facilities that is illustrated in MUTCD Figures 2G-2 and 2G-3, but it is not specifically described as being based on driver decision-making.*)
- The practitioner's DOT required lighting where it thought that the access movements would take place, but lighting is not necessarily associated with the location of the signage. Rather, the practitioner stated that there is anecdotal data to suggest that the movements take place in response to the signage, perhaps a quarter-mile before the lighting, so the lighting may not be in the optimal location to illuminate the decision points where lane changes occur.

Comparison of Shared and Unidirectional Access

Question 1: Are there differences in preferred at-grade access for single-lane versus multilane treatments?

The three practitioners who responded to this question indicated that there was little or no difference in preferred access for single-lane facilities compared to multilane facilities. The provided access may be the same for both types of facilities, or any variations in access are due to other factors instead of the number of lanes.

Question 2: Does the preferred access treatment change at a particular volume or level of demand?

There was not a clear pattern in the three answers given to this question. The response for one facility indicated that higher access volumes necessitated longer merge lanes, but the decision to provide longer merge lanes also depended on speed and congestion in the general-purpose lanes. Another facility had a slightly longer weave zone at one access point with higher demand, while the third facility had no difference in access.

Question 3: What are some tools/guidelines/information sources you did not have that would have been beneficial?

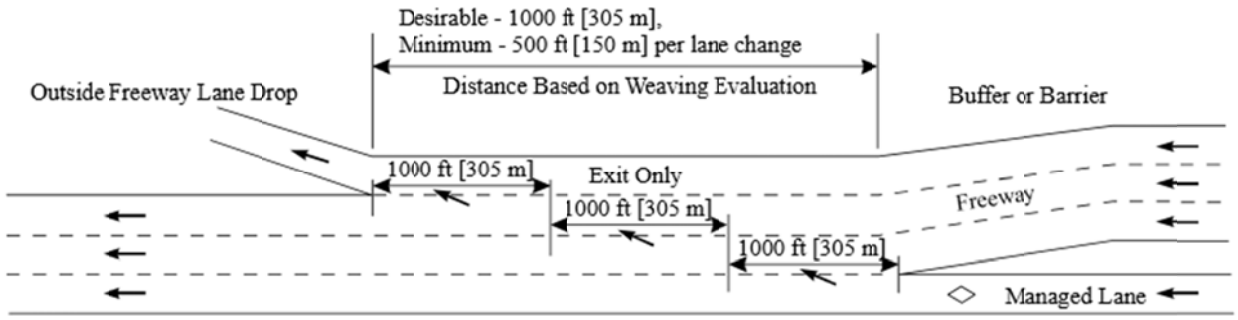
Answers to this question followed similar themes to the corresponding question in the previous two categories. One respondent indicated a desire for national guidelines on weaving distance and length of weaving zones. Another discussed the practice of providing open access as the baseline condition and only restricting access in certain locations as needed. The final respondent indicated a desire to have the results from his agency's ongoing access study on another facility in the region.

Summary

Eight practitioners were asked to provide specific insights about access to and from their managed lane facilities. Six of the eight practitioners responded, providing information about nine existing facilities, including two that have planned changes to their access.

Access openings tend to occur 1 to 3 mi apart, though the reasons for providing access of a particular type or in a specific location are varied, ranging from policy decisions to safety or operational considerations. Each agency determined which factors were most important to a given facility, and the factors chosen varied from one facility to another. Weaving distances were typically between 600 and 1200 ft per lane change, which is consistent with many of the existing guidelines and research recommendations. Performance of access is not necessarily reviewed on a routine basis, but agencies are responsive to feedback from drivers and policymakers. The practitioners in this study were almost universally interested in more guidelines for weaving, either for length of weaving areas or for appropriate weaving distance for lane changes between managed lane access and general-purpose access. In the case of the latter, recommendations for spacing between general-purpose ramps and managed lane access in previous studies and current guidelines (*2, 4, 5, 30, 32, 33, 34, 35*) have suggested that cross-facility weaving areas should provide between 400 and 1000 ft per lane change, depending on anticipated traffic volumes and other conditions, and the 1000-ft value is the common recommendation among the more recent references, though there may be a need to

further promote the research findings to other agencies that are not familiar with them. An example of the 1000-ft per-lane distance for the termination of a managed lane is shown in Figure 43.



Source: Adapted from (*31*)

Figure 43. Weaving distance at termination of a managed lane.

Respondents who worked with continuous-access facilities discussed the operational benefits of open access, as well as the simpler analysis process to identify locations for restrictions as compared to having to justify locations for access. Drivers on those facilities also prefer greater access, and respondents commented that safety is not negatively affected. The respondents considered operational characteristics in the evaluation of continuous access, though safety and revenue could be important factors as well. Documentation of previous experiences was highly desired so that practitioners of future projects can learn from the decisions made on previous projects. Specific examples include configuration of access openings, signing for continuous access, and appropriate lighting for both signing and access maneuvers.

The practitioners in this study indicated little difference in preferred access for shared weaving versus unidirectional access for single- or multilane facilities. There was also not a clear practice for making changes to access based on traffic volumes, though the respondents would be interested in learning more about how other practitioners made their decisions.

EXISTING GUIDANCE

Introduction

A review of existing written policies and practices was conducted to determine what defined recommendations or guidelines exist for providing access to and from managed lane facilities. Much of the information available was compiled during Phase I of the project, but some additional sources were identified during Study 5R.4. Relevant portions of selected written policies and practices related to the practitioners' survey responses are summarized in the following sections.

Selecting the Type of At-Grade Access to Provide

Caltrans Traffic Operations Policy Directive (TOPD) 11-02 (*2*) states that consideration should be given to both limited and continuous access when planning managed lanes. The TOPD goes on to say that the choice of access type is based on a general evaluation of the performance and management benefits for the entire freeway as well as the capital costs of building and operating the facility. A summary of design, cost, and performance considerations for the two types of access designs is provided in the document. Whether access is limited or continuous, the resulting project must meet design and performance requirements, which are described in the TOPD.

Ultimately, the type and location of proposed access on California's managed lane facilities is determined by an operational analysis, which, combined with a safety analysis, is part of a required traffic engineering study. It is expected that an iterative process will be used. For example, an access opening using the simplest design and minimum lengths might be evaluated first. If the analysis supports this concept, then no further analysis of that location is necessary. Otherwise, the process will continue until an appropriate concept is identified or all concepts are exhausted. The iterative process may require consideration of the following modifications or features (not necessarily in this order):

- Increased weaving lengths.
- Alternative types of access.
- A second managed lane in the vicinity of the opening.
- Relocation of the access opening.
- The addition of auxiliary lanes connecting ramps on the general-purpose lanes.
- The use of drop or direct connector ramps.

For facilities with limited access, Caltrans says that existing interchange spacing is the primary consideration for determining the location of access openings. An equally important consideration is the existing and expected location of mainline operational bottlenecks and geometric constraints that produce recurrent congestion and queuing along the general-purpose lanes. Access openings should be located and designed such that they will perform at level of service (LOS) C or D. They should not produce adverse impacts to managed lane and general-purpose lane performance, nor should they be placed where recurrent general-purpose lane congestion is expected. A limited-access facility may be converted to a continuous-access facility if the conversion is funded by the project sponsor requesting the change. A traffic study, as described in this directive, will be required for any conversion project.

The NDOT *Managed Lanes and Ramp Metering Design Manual* (*4*) says that access along a concurrent-flow lane may be allowed at any point (continuous access), or access may be restricted (limited access). If access is restricted, designated intermediate access zones or direct-access ramps will be utilized. A traffic operations analysis is required to identify and justify the proposed access option, including the types, locations, and opening length of proposed access locations to limited-access facilities on concurrent-flow lanes. The NDOT manual states that, generally, an access opening should be provided before and after system-to-system interchanges and other major interchanges. A summary of the attributes of some common access options is provided in the NDOT manual.

The FHWA *Priced Managed Lane Guide* (*36*) states that the type of at-grade access opening that is selected will depend on the existing and planned roadway geometrics and the amount of traffic expected to use the opening. In all cases, openings should be located and designed in a way that will not produce adverse impacts to the managed lanes and the parallel highway lanes. The locations of at-grade access openings need to be closely coordinated with highway entrance and exit ramps and allow adequate room for motorists to complete weaving movements when moving between the general-purpose and managed lanes and an entrance or exit ramp.

Distance Between Successive Ramp Terminals and Length of Weaving Sections

Chapter 10 of the AASHTO *Green Book* (*7*) provides guidance on spacing between freeway access points. While this guidance is intended for general-purpose access, the principles can be applicable to managed lanes. To provide sufficient weaving length and adequate space for signing, a reasonable distance should be provided between successive ramp terminals.

Figure 10-68 of the *Green Book* presents recommended minimum ramp terminal spacing for four various ramp-pair combinations as they are applicable to interchange classifications; the EX-EN and EN-EX combinations are particularly applicable to managed lanes access. The stated minimum distance for EX-EN pairs on freeways is 500 ft. For EN-EX pairs (weaving sections) on system-to-service interchanges and service-to-service interchanges, the minimum distances are 2000 ft and 1600 ft, respectively. EN-EN and EX-EX pairs on freeways have a minimum distance of 1000 ft between successive ramp terminals. The capacity of weaving sections may be seriously restricted unless the weaving section has adequate length, adequate width, and lane balance. The reader is referred to Section 2.4.6 of the *Green Book* for procedures for determining weaving lengths and widths and referred to the HCM (*26*) for capacity analysis of weaving sections.

Caltrans (*2*) recommends a buffer/barrier opening of at least 2000 ft and a weaving distance of at least 800 ft per lane between the opening and the nearest freeway entrance or exit ramp. Examples of the dimensions of these openings for weave zones, combined weave lanes, and separated weave lanes are shown in Figure 1.

NDOT (*4*) states that the following criteria are desired for frequency of access openings for different types of managed lanes:

- For HOV lanes, provide minimum of 2 mi between access openings.
- For express lanes without toll, provide minimum of 4 mi between access openings.
- For priced managed lanes (e.g., HOT), provide minimum of 2 mi between access openings.

Both weave zones and weave lanes are required to have a minimum length of 2000 ft. A minimum of 800 ft per lane change distance should be provided between at-grade access and the ramps. The specific distance should be determined based on weaving analysis.

Appropriate Ways to Evaluate and Consider Effects of Limited Versus Continuous At-Grade Access

Caltrans (*2*) states that the design decision between continuous and limited access will be more appropriately based on the site-specific types and patterns of traffic and the ability to manage this traffic using the access most appropriate and cost effective for the corridor, rather than safety or throughput performance. Caltrans provides a list of considerations for each of the two types of access based on categories of cost, mobility/safety/performance, and enforcement.

NDOT (*4*) advises that access along a concurrent-flow lane may be allowed at any point (continuous access), or access may be restricted (limited access). If access is restricted, designated intermediate access zones or direct-access ramps will be utilized. A traffic operations analysis is required to identify and justify the proposed access option.

Many other current reference documents, both state and national guidelines, describe differences in the characteristics of the two types of access, but little is said about how to determine which of the two types is most appropriate for a particular managed lane facility, and limited at-grade access is often compared to direct-access ramps, not unlimited or continuous access. The FHWA *Priced Managed Lane Guide* (*36*), for example, provides the following description:

> Restricted at-grade access to a striped or barrier-separated managed lane is a cost-effective approach to providing controlled access to the managed lane facility. At-grade access opening control ingress and egress to and from the managed lane, minimize traffic service impacts in the managed lane, and control weaving movements on the parallel highway. While they limit the need for expensive ramp structures, they may require additional pavement area, and can require modifications to existing bridges and sign structures. Because access is limited to certain locations upstream and downstream of interchange ramps, there is the potential for bottlenecks to form near access points. … Several projects have moved forward with less restriction on access, employing more limited areas where traffic cannot weave back and forth between the managed lane and the general-purpose lanes. ... In [those] cases, frequent and appropriately located toll zones limit violations, and the violation levels to date have been acceptable without added enforcement. Additionally, near-continuous-access designs permit weaves between the managed lanes and general-purpose lanes to be more distributed, thereby reducing the effect of conflict at access openings. Finally, the need for signage is reduced, which in turn can be a positive effect upon capital cost requirements.

The AASHTO *Guide for Geometric Design of Transit Facilities on Highways and Streets* (*37*) similarly says that direct merge or at-grade access represents the most commonly used intermediate treatment with concurrent-flow bus/HOV lanes. Two types of approaches are used in North America: unrestricted access and limited access. Unrestricted access usually is used with bus/HOV facilities that operate only during the peak periods, which allows the bus/HOV lane to revert easily to a general-purpose lane at other times. Where access is restricted, a relatively inexpensive intermediate access treatment is the use of slip ramps. Most

slip ramps represent a break in the buffer delineation and allow ingress and egress. For higher-volume locations, slip ramps can be provided with weave lanes. Potential safety issues should be examined in the design.

Differences in Preferred Access Treatments for Certain Conditions

Practitioners were asked about whether certain types of access were preferred for certain conditions, such as single-lane versus multilane facilities or a particular volume or level of demand. Their answers indicated that there are not typically any preferences for those conditions, but other factors or analyses drive those decisions, as described in the previous sections. This is consistent with the information available in existing manuals and guidelines, as a particular treatment is not specified for a given condition, though the number of lanes and/or the volume may be part of a broader analysis. The Caltrans policy (*2*) mandates that several factors will be included as part of the analysis for making decisions on access. The following information and assumptions should be identified and utilized as part of the traffic study:

- Design year peak-hour volumes for the managed lanes, general-purpose lanes, and adjacent general-purpose ramps. The design year should be 20 years from the date when the project is scheduled to be completed and opened to traffic.
- The design year peak-hour volume of vehicles expected to use access locations.
- The types of vehicles expected to use the freeway facility (e.g., transit or trucks).
- Geometric constraints on the managed lanes and general-purpose lanes, including known and expected bottlenecks and associated queues.

The operational analysis should be performed using a methodology that is acceptable to the district and the project sponsor. The operational analysis should:

- Evaluate the characteristics of the entire freeway facility, including both the managed lanes and the adjacent general-purpose lanes.
- Include a merge/diverge analysis of any drop ramps or direct connectors that may be utilized on the managed lane.
- Evaluate the operational impacts of access openings on a limited-access facility.

Additional Topics Suggested by Practitioners

The responses to the final question of each category in the practitioner survey allowed the respondents to offer any other ideas or suggestions on desired guidance. Some, such as length of weaving sections, have been mentioned previously. Other topics, such as recommendations for lighting requirements, are not necessarily access design elements but could contribute to improved safety and/or efficiency. Little to no information on these topics was found in the references available for this review, but a summary list of those topics is provided here for documentation:

- Congestion-based guidelines for length of the at-grade weaving area at the access point and for weaving distance per lane change.
- Effects of buffer vs. added lane width on operating speed, speed differential between general-purpose and managed lanes, and capacity/throughput.
- Location/design of access points based on driver expectation.

- Recommendations based on driver decision-making for signing and lighting for continuous-access facilities.

Summary

Much of the information on managed lane access that was found in existing design manuals and guideline documents appeared to be derived from, or could eventually be traced to, a limited number of references: the AASHTO HOV guide (*3*), NCHRP Report 414 (*38*), and the HOV facilities manual by Fuhs (*35*). In addition, those three documents also share common content. Some unique details have been added to specific portions of various state and national guidelines, but the general principles were similar across all of the sources available to the research team, and most were based on prior HOV experience. This provides consistency in design for a selection of key design features, but it does not provide many details on the underlying basis for those design guidelines. As a result, practitioners tend to rely on their own experiences for engineering judgment to make decisions on site-specific applications not found in existing guidelines. Practitioners in this study stated a desire to have more guidelines available to inform their decisions, and these guidelines would be based on practices of other practitioners who have shared their experiences and the outcomes of their decisions.

SUMMARY OF FINDINGS

Lessons Learned from Current Practice

The number of documents containing written guidelines or policies for the design of managed lane access has increased in recent years, but much of the information found in those documents seems to be based on earlier guidelines dating back a decade or more. In some cases, states have conducted studies to help inform them on a particular topic for their region, but results from national research to help populate existing and future guidance did not appear to be widely available.

The practitioners participating in this study use a variety of tools and guidelines, both regional and national, and indications are that their facilities operate acceptably. However, there was a consistent message from the respondents that they would like to be better informed on practices in other jurisdictions to see what options they had not previously considered or take advantage of lessons learned on prior projects to improve their confidence that the access they have provided is the most appropriate for the facility. In particular, there are questions about sufficient weaving distances between managed lane access and general-purpose access, as well as appropriate lengths of weaving zones for shared ingress/egress. Guidance on how to determine what factors should be considered when locating and designing access would also be beneficial since there are many potential (and potentially competing) factors that could be used in the decision; while there may not be a single right answer, agencies should be able to consider what factors (e.g., operations, safety, revenue) are most appropriate for a given facility and then prioritize the factors most important to them.

Respondents stated a preference among drivers for continuous access, and the responses to this questionnaire indicate a corresponding preference to accommodate that design when

possible. However, it is also important to provide practitioners with the information necessary to consider the needs of a particular facility, accounting for operational characteristics, safety concerns, revenue and enforcement considerations, and design constraints. Documentation of previous experiences is highly desired on these topics as well.

Given these findings, the questions posed in the study objective can be answered as follows:

- *What are appropriate ways to evaluate and consider impacts of restricted and continuous at-grade access?* Operational effects should be the highest priority. Safety, economic, and enforcement effects are also valid considerations, but they often exist in conjunction with operations. For example, if a proposed access point or series of points cause bottlenecks or do not allow managed lane drivers to use their desired general-purpose entrance and exit ramps, then the access is not serving its purpose and the effects of other factors may not be fully appreciated. It is also important to have appropriate context when making decisions on operational effects. Managed lane and general-purpose lane operations are intertwined, so decisions about managed lanes should not consider those lanes as if operating in a vacuum. In addition, the context of time must also be considered; an access point that operates satisfactorily on Day 1 or in Year 5 may not maintain that level of operation at the end of the expected design life, so all of the decision makers need to have the same expectation of the time horizon being considered.
- *What level of operational analysis is needed during the planning phase to determine operational feasibility?* There is not a great deal of existing guidance available to answer this question, but key items that should be considered for the analysis include level of service and avoidance of general-purpose weave turbulence such as bottlenecks near major interchanges. This suggests a level of analysis that looks not only at the entire corridor but also at the immediate area surrounding each proposed access point or driver decision point. The research team will look to identify any available tools from the HCM or other resources that could be cost-effective ways of performing these analyses, but as agencies develop policy directives requiring specific analyses, new research will likely be needed either to better adapt existing tools for this purpose or to develop new tools to accomplish the needed analyses.
- *What are appropriate criteria for determining ingress/egress locations and impacts on pricing demand?* Effects on pricing demand are secondary to operational effects, but if an ingress or egress location is operationally sound, then that access point will also have many of the basic characteristics needed to make it economically beneficial as well. More detailed criteria that are specifically related to pricing effects would need to be explored in a study focused on those effects.
- *What are preferred approaches to at-grade access for different levels of demand associated with single- and multilane concurrent-flow treatments?* There appears to be little preference at this time, either in written guidance or in actual practice, for a specific treatment to correspond to a given set of conditions. Increasing the length of access points and providing weave lanes are two common treatments that are available for facilities with limited access that have increased demand. Providing or converting to continuous access is also an option, but each option should be considered in the context of an operational analysis to determine which treatment is best for a particular facility (or specific location within that facility).

Recommendations for Guidance Updates

Some of the items noted above have been addressed through NCHRP Research Report 835 where sufficient information exists to describe a common or preferred practice. Some examples are as follows:

- Clearly identifying and referencing weaving distances of approximately 1000 ft per lane change for moving from managed lane access to general-purpose access.
- Describing current best practice for the length of access openings, whether unidirectional or shared weaving zones.
- Clarifying the role and description of various types of at-grade access and their context (i.e., single or dual concurrent lanes with commensurately different demand volumes, and implementation application for HOV-to-HOT conversions or new lane construction). These clarifications are particularly appropriate for the application of weave zones and weave lanes.
- Providing a list of potential factors (e.g., operational, economic) that could inform the decision on the location and type of access, and encouraging practitioners to prioritize the factors appropriate for a given facility before determining access details.

CHAPTER 6

KNOWLEDGE GAPS

OVERVIEW

The information in this chapter documents knowledge gaps identified by the research team in the development of the guideline materials. In some cases, these identified gaps are related to subject matter, where limited documentation exists of prevailing practice. In other cases, gaps are related to the lack of syntheses that pull together the wealth of commonly available information so that the practitioner can more easily grasp what practices are more prevalent and why. Knowledge gaps are categorized and presented here to correspond with chapters in the *Guidelines for Implementing Managed Lanes* (*1*), or when a gap reflects the entire system, it is provided in the initial section of this chapter.

OVERALL ISSUES

1. **Update schedule for the *Guidelines for Implementing Managed Lanes* document** (*1*). The *Guidelines for Implementing Managed Lanes* document reflects knowledge as of the time it was prepared. New knowledge and valuable experiences will continue to be gained, and the profession would benefit if the guidelines would be updated to reflect this information. Creating an update schedule, along with identifying the group(s) responsible for the updates, would help to ensure the document's relevancy for the future.

2. **Effects of 2015 transportation legislation.** In late 2015, Congress agreed to a new multiyear transportation bill called the Fixing America's Surface Transportation (FAST) Act. Several sections of the FAST Act will have an impact on managed lanes along with tolling and other related components. Revisions to *Guidelines for Implementing Managed Lanes* (*1*) may need to consider how the FAST Act affects the design, implementation, and operations of managed lanes.

3. **Similar guide for arterial managed lanes.** The *Guidelines for Implementing Managed Lanes* (*1*) focus on the implementation of managed lanes on freeways. A companion document is needed for the implementation of managed lanes on arterials.

4. **Public support and acceptance.** FHWA has developed various documents over the years (at least three since the 1970s), with the most recent one addressing express lane marketing and outreach guidance. Key components of these guides, coupled with widely different project launch experiences from various express lanes, need to be summarized for easy reference since tolling has become so important in gaining public acceptance.

5. **System-wide network issues.** Increasingly, systems or networks of managed lanes are emerging in large regions like the five-county San Francisco Bay Area and smaller (yet highly congested) metropolitan areas like Charlotte, San Diego, and

Austin. A wide range of policy, design, operation, and agency partnering needs arise in these areas. Consistency becomes important while preserving the need to customize operations and designs for each corridor. System-wide guidance is lacking in most guides to date and needs additional research to identify best practices for several topical areas (e.g., techniques for distributing information to users, such as signs, websites, etc.).

INTRODUCTION

6. **Inventory of all managed lane projects on freeways.** A gap currently exists in an updated inventory of current projects and their key attributes that both combines HOV lanes and priced managed lane projects nationally and with Canadian experience. This category of data need represents the most commonly requested category of information, based on feedback from FHWA and TRB staff affiliated with managed lanes. The last such updating effort was performed by FHWA through the Managed Lane Pooled Fund Study in about 2008. This report captured general project information on two sets of spreadsheets. Based on a quick assessment among state DOTs in November 2015 as part of this research effort, the mileage has increased about 10 percent since then, and many of the planned projects found in the 2008 inventory have been built. Based on information sharing through the respective TRB committees, a much larger number of projects are planned, but no data exist to document these. In the past, detailed inventories occurred at least every 10 years.

7. **Updated maps and graphics.** As a result of the gap above, there is no readily available source of graphics that synthesize commonly applied best practices, whether these be a national map showing the number of projects by metropolitan area, number of locations with part-time versus full-time operation, number of locations with part-time shoulder use, number of locations where buffers or pylon/delineators are applied, or a host of other needed information that concisely frames experiences across a broad range of common operational and design attributes.

8. **Common performance data**. A similar gap exists in the ready availability of common performance-based information about all managed lane projects on controlled-access facilities. Consequently, it is difficult to sum the collective operational experiences that can inform designs and operational efficacy. There is a need for a common method of aggregating such data for comparative purposes. This is also related to listing goals and objectives for a particular project. It is unclear to what extent this supporting information is documented and compared in recent priced managed lane projects. This information is needed to expand the introductory discussion on this topic and enable decision makers to have an example to use on future projects.

9. **Use of terms to describe facility types**. Some of the technical terms applied to specific types of managed lanes need to be reviewed, perhaps beyond panel members with a broader cross-section of practitioners. There are multiple terms for some types of designs. One example includes concurrent-flow facilities, which are variously called contiguous lanes when applied to a part-time setting (in California), diamond

lanes (in Texas), and HOV lanes (in other states). Washington State refers to a transit station located within the freeway as an in-line station, while others refer to this approach as an on-line station. Some older terms in prior guides have dropped out of favor, such as exclusive facility.

10. **Active traffic management**. Applications addressing active traffic management/ITS treatments are largely missing from documentation except for the two major new examples on I-35W in Minneapolis and I-5 in Seattle. A much wider application of ITS has been practiced on many corridors since the mid-1980s, yet limited experience has been documented, including early applications of providing real-time information on operating status (common to reversible and contraflow lanes); changing eligibility requirements; dynamic lane assignment (i.e., when a left lane becomes an HOV while the right shoulder provides hard shoulder running, such as I-66 in Virginia); travel time and time savings (applied on many projects including Houston's reversible lanes); and incident management, enforcement, and traffic operations center monitoring tools applied on a wide range of projects.

11. **Latest financial performance from priced express lanes**. The latest FHWA *Priced Managed Lane Guide* (*36*) does a good job of synthesizing current financial performance, but many agencies are feeling that their performance is still preliminary until their projects have a longer track record. This gap may require revisiting those data sources and collecting the latest financial performance for these projects.

12. **Decision-making**. The need to more clearly define how decision-making is occurring in the current context is lacking from available references. An understanding of decision-making for both formal project development and more modest operational changes is a particular need given the wide-ranging number of legacy projects being updated with latest technologies and tolling treatments. Feedback from practitioners surveyed in the 15-49 research effort indicated that guidance in best practice for addressing operational changes is a particular need that could benefit a large number of projects in saving time and effort. A synthesis of practice occurring from the recent round of UPA/CRD projects, coupled with P2 and P3 partnering, seems to be a way of grappling with this topic, since it reflects current and likely future decision-making within context to the feasibility, National Environmental Policy Act (NEPA), and formal project development process. The closest example of a matrix that may be used to help in this discussion is in the FHWA *Priced Managed Lane Guide* (*36*): Table 3-1: Priced Managed Lane Project Activities and Responsibilities.

PLANNING CONSIDERATIONS

13. **Legislative and policy considerations**. There is an overall gap in guidance for the policy and legislative considerations when implementing managed lanes, particularly on the state and local levels. Examples include how enforcement agencies adjudicate enforcement, how excess toll revenue is addressed, and how possible liabilities concerning performance degradation (e.g., travel speeds below 45 mph) on newly built facilities are mitigated. Very little guidance or examples are available from national resource literature. The Federal Highway Administration provides guidance

relevant to particular sections of the U.S. Code based on the major reauthorizations of the federal surface transportation program; however, most state DOTs and regional agencies have little guidance for the application of policy frameworks that could impact the planning and operation of their managed lanes.

14. **Conceptualization of the impact of design and operational options**. During the pre-NEPA, regional, and corridor planning processes, agencies are often asked to consider a wide array of managed lane options (i.e., design and/or operational variants to assess feasibility). The process for assessing options is different and separate than the process for evaluating an environmental review. Stakeholders want questions answered about performance using specific metrics, including but not limited to number of safety incidents, volume, mode split, and revenue generation. Traffic microsimulation analyses attempt to provide answers but are often budget- and time-intensive activities that limit a proper analysis to only a few select options. The managed lane planning process can benefit from an earlier understanding of how key variables impact performance, particularly for conceptual planning. For example, capacity on a four-lane freeway is reduced by 6.5 percent given a scenario with a 1500-ft cross-weave distance (length between a freeway on-ramp and a managed lane access point) and a crossing rate of 600 vehicles per hour into the managed lane, based on research from NCHRP Web-Only Document 191 (*39*). In past planning guidance for HOV lanes, rules of thumb were often offered to help limit such early analyses, with recognition that not all projects might fit the parameters exhibited on the subset of project experiences that guidance was based on. General questions about the relationship between toll rates and available capacity are popular for priced facilities. For example, are toll rates for two-lane managed lanes half, one-third, or one-fourth of the rates compared to single-lane facilities? The relationship between toll rates and available capacity is theorized to be non-linear. Stakeholders want to know high-level, big-picture impacts when considering many options early in the planning process.

15. **Integration of carpooling and travel demand management (TDM) programs**. In addition to the design of managed lanes, the influence of carpooling and TDM programs also has an impact on the performance of managed lanes. To what extent should agencies promote carpooling on the managed lanes? What type of incentives work the best? How do agencies integrate carpooling into their programs? An example of integration could be a trip-based rewards program (e.g., what the Los Angeles I-10 and I-110 ExpressLanes do by offering a toll-free car trip for every set of transit trips).

16. **Anticipation of the impacts of emerging technologies**. Agencies are inquiring about the long-range impacts that emerging technologies and changing user expectations could have on managed lanes. More operators are using mobile applications to help users pay tolls, declare occupancy status, and find riders to form carpools. Drivers of automated and connected vehicles may seek to utilize existing managed lane infrastructure for travel time and reliability benefits. No guidance is currently in place for agencies to contract with outside entities to integrate emerging technologies (i.e., what content should be used in a request for proposals, or what real-time data streams

should be provided [e.g., facility speed] to developers and manufacturers to integrate additional products and services).

17. **Environmental review**. Beyond NCHRP 414 (*38*), significant research has not been conducted recently on the topic of handling environmental review during the planning process. A critical issue for managed lanes is the coordination of the overall public outreach campaign with the engagement efforts that are specific to environmental review. Marketing of specific managed lane alternatives is most often prohibited for environmental review activities. Some agencies were made to effectively coordinate NEPA and public outreach by labeling an alternative that may or may not be a managed lane, a "future transportation corridor." Given this regulatory framework, what types of events and activities are appropriate to have? What type of coordination is usually required from FHWA? If there are state-specific reviews (e.g., California Environmental Quality Act), then what steps should be followed in those instances? Successful practices could be shared by agencies charged with planning managed lane facilities.

18. **Preservation of transit benefits**. As HOV lanes shift to incorporate pricing and are opened to a more diverse mix of users, renewed interest is being given to rethinking how transit is best served. Private employers and entrepreneurs are experimenting with on-demand services that are not easily recognizable compared to traditional buses. Some projects have integrated new transit services, facilities, and policies that are complemented by pricing, and lessons learned from a wide range of examples now need to be incorporated—from both early examples (e.g., I-15 in San Diego) and more recent projects including the 95 Express in Miami, I-35W MnPass Lanes in Minnesota, I-405 Express Toll Lanes in Washington State, and US-36 Express Lanes in Denver.

DESIGN ELEMENTS

19. **Pullouts.** When the implementation of a managed lane uses the existing shoulders for travel lanes, provision for disabled vehicles can be provided by pullouts or refuge areas. There is a need for guidelines on the design and operation of such managed lane features. The appropriate spacing, geometric design, and operational characteristics of these refuge areas should be researched to determine how those already constructed (in the United States and elsewhere) are operating and provide guidance to locate and design future pullouts for optimal performance. Additional considerations may include:
    - A perceived increase in disabled vehicles in many urban areas, possibly due to economic conditions where people are keeping their vehicles longer, increasing the likelihood of mechanical breakdown.
    - Desired spacing and optimal location for pullouts.
    - How to handle the situations when the desired spacing is not available due to the constraints that do not allow sufficient width of right of way, nor expansion of the right of way, to provide the space for the treatment.
    - Desire of police to use pullouts as an enforcement area, both for checking compliance with the restrictions on lane use and for crash investigation, and what

effect doing so has on geometry of the site and safety for the enforcement vehicles.

20. **Enforcement.** There are guidelines in selected states on how to provide the necessary space in the cross-section for enforcement activities, but they are primarily for observation areas and not for pursuit or apprehension, and the guidelines are not widely distributed. A more broadly applicable set of guidelines with greater detail is needed for the rest of the country. Similarly, what are the enforcement needs and scenarios if there is no inside breakdown shoulder to monitor and apprehend? Will a dedicated monitoring or enforcement area work instead? An evaluation of various enforcement treatments would be useful in helping decision makers understand trade-offs and determine which one is best for them.

21. **Safety.** Currently, tools that can be used to evaluate the effectiveness of certain treatments and the safety performance of a freeway corridor are available or in development (e.g., HSM [*14*], Interactive Highway Safety Design Model, etc.); however, none of those tools specifically consider managed lanes. Adding modules or treatments to existing tools would greatly improve the ability of those tools to evaluate managed lanes.

22. **Effects of weaving sections on managed lane operations.** The profession has guidelines on the appropriate length of access openings for restricted-access facilities and guidelines on how much distance per lane change should be provided for cross-facility weaving. What is not well known is what happens to managed lane operations if these are not provided. For example, how sensitive are the effects on operations due to the proximity of the general-purpose entrance (or exit) ramp and the managed lane entrance (or exit) ramp with respect to demand? A growing number of projects have found ingress and egress requirements to represent a critical feature needing guidance based on safety experience and the latest traffic analysis tools.

23. **Additional access-related considerations**. The practitioner interviews on managed lane access (see Chapter 5) provided valuable insights into current practices that were included in the guidelines document (*1*), but the practitioners also raised other questions that would be best answered through future research on subsequent projects. Not all of these are purely design related, but they are related to the operational effects of the access design. Based on responses from the practitioner survey and discussions among the research team, a number of potential research topics emerged, many of which were applicable for buffer-separated facilities. Potential research topics include:
    - Preferences and trade-offs of combined versus separate ingress/egress.
    - Preferences and trade-offs of weave lanes versus weave zones.
    - Comparison of access (ingress, egress, or shared) configurations (length and striping patterns) for single- and dual-lane buffer-separated facilities under a variety of implementation settings that range from conversions to new construction.
    - Appropriate use of pylons in conjunction with slip ramps.
    - Appropriate signing (type and placement) for continuous-access facilities.

- Optimal placement of lighting adjacent to managed lanes access.
- Data needs for operational analysis of managed lanes access.
- Investigation of different types of direct-access ramps in current use, and the best type of direct access for certain conditions.

TRAFFIC CONTROL DEVICES

24. **Sign sequencing.** The MUTCD does provide some layout illustrations for the sequence of signs leading up to managed lane access points. This guidance is based on principles of regular guide signing and HOV lane signing. For priced managed lanes, however, the driver decision is more complicated due to the cognitive effort of assessing potential travel time savings versus cost. For this reason, it is likely that drivers would benefit from earlier advance signing and from repeated presentation of key information such as price. The order of signs in the sequence is also not clear. In focus groups conducted for TxDOT (*40*, *41*), the groups were evenly split on whether they would like to see the price sign before the guide sign showing exits served or before the estimated travel time savings sign. This research would test different sequences to measure the choice behavior of drivers and the speed of those decisions. Sign sequencing should explore what may be considered as the upper limit for driver information needs. The research should try to capture some or all of the following examples, perhaps in a 5–10 second timeframe approaching a priced managed lane entrance:
    - Advance guide signing (left exit, 0.5 mile, etc.).
    - Type of facility (identifier banner).
    - Advance exits/exit numbers.
    - Time savings to downstream destinations.
    - Regulatory:
        - Eligibility (who is free or discounted and when).
        - Exemptions (motorcycles, low-emission vehicles).
        - Pricing to downstream destinations.
        - Allowable tags on facility (pictographs on top).
        - ETC only—no cash.
        - Pay-by-plate (if and when allowed).
        - Prices for other sized vehicles.
        - Truck restrictions (if any).
        - Occupancy requirements (if any).
        - Hours of operation.

25. **Information needs.** If conventional toll roads and prior HOV lanes are used as requisite parallels, the following practices are occurring to reduce signing clutter:
    - Definitions are posted in advance of and after sign sequence as reinforcement (HOV = 2 or more persons per vehicle).
    - Abbreviations or pictographs are used (HOV2+ or car symbol with persons in car).
    - Only limited toll rate information is posted on toll roads, typically representing minimum cost or cost range. Secondary vehicle classes may not be posted at all,

or may be posted on a schedule at the toll plaza. (Could some of these informational items be relegated to apps or website?)

Most important to this research would be answering the following: What is the highest to lowest level of information needed? What can and should be relegated to other means of obtaining the information? It seems the profession is already setting precedent by saying in current guidance that only two or three downstream destinations can be included on a dynamic message sign (DMS). So an order of precedence is already being sorted out, if for no other reason than limits on sign size.

26. **Amount and type of information presented to motorists on one structure.** The practice of placing managed lane information on the same structures as mainlane signs is certainly common. These structures become very crowded, and drivers may become overwhelmed, resulting in erratic last-second maneuvers. (This issue is related to the research idea on sign sequencing; there is likely more information than what will fit on just a sign column or bridge.) This research needs to explore the limits of urban driver comprehension and should sort out what is most important and what should *not* be addressed on signs (such as apps, websites, or off-roadway media). It should also explore the level of information possible at different design speeds (e.g., 70 mph vs. 40 mph). This issue may not be unique to managed lanes because variably priced toll roads, active traffic management (ATM), DMSs that address Amber Alerts, and a host of other freeway operational strategies are facing this same scenario.

27. **Specific sign legends.** The terminology used for managed lanes differs across the United States because many of the existing facilities were in the planning stages or already built when the 2009 MUTCD (*42*) was released. There are legacy terms and signs on these facilities that could be confusing to motorists in a region with new managed lanes coming online. Examples of these include:
    - Terms to refer to pay-by-plate license plate recognition systems.
    - Communication that a transponder is required even for no-toll HOV users. The phenomenon in some facilities to require HOVs on the facility to have a transponder to pay no toll has introduced a new element of complexity. The complexity rises significantly on those facilities that also allow plate tolling. At the time of this writing, FHWA is pursuing a project titled Best Practices for Signing on a Multisegment Managed Lanes Network: DTFH61-12-D-00048 T-5007. Initial results from this study indicate that users are having difficulty understanding the concept that some facilities have both an occupancy requirement as well as a transponder requirement to be considered an HOV for tolling eligibility. Additional study is ongoing, and this report, when published, may provide additional insight into signing for HOVs under this condition as well as for multisegment networks.
    - Communication that license plate payment may result in a higher charge.
    - Terms that refer to “branded” or promotional names. Specifically, the term “express lanes” has still not been tested for comprehension, particularly in regions where legacy systems exist. Complicating the situation is that this term was more or less dedicated to priced managed lanes at a point in time (2008) when all

projects were serving long-distance trips with extremely restricted access. However, this condition is no longer true, with an increasing number of projects operating with up to 75 percent open access (Minneapolis) and some without any restrictions at all (Bay Area). "Express lanes" may still work insofar as the facility being left-oriented relative to the general-purpose lanes, and most will continue to have limited access like the old express lanes from the 1950s. The issue of terminology testing and consistency is hardly unique to priced managed lanes; California is still trying to retrofit its carpool lanes to HOV lanes on signing and markings, even though this required change dates back at least 6 to 8 years. Meanwhile, California motorists have a 30-year legacy with the prior term.

- Appropriate order and amount of information on signs. Regulatory signs describing times, vehicles, and payment restrictions can become very wordy. Research is needed to understand the priority of these and other strategies to spread out this information to avoid driver overload.
- Guidance in the MUTCD. The MUTCD lacks guidance on when and where to post NO CASH signs. Actually, the MUTCD lacks guidance for a host of related regulatory information noted on the above bulleted list, at least for managed lanes.

28. **Exit numbering.** Exit numbering could be useful shorthand for managed lane access points and for signs indicating access to upcoming mainlane exits. Exit numbers could reduce the amount of information on signs. There is a need for focus groups to determine if exit numbers can serve in lieu of exit names. Only one managed lane (i.e., I-495 Long Island Expressway) fully endorsed this approach, and no other projects have followed. Guidance, as well as sample layouts, needs to be developed to implement this practice. Research is needed to understand when and if drivers would utilize exit numbers.

29. **Guidance for reversible-lane traffic control devices (TCDs; most critical is vehicle-arresting barriers)—applications and approaches.** TCDs are safety-critical for reversible lanes, yet there is no definitive guidance on placement in context with other TCDs. Also needed is guidance on frequency of gates when operated to close off an entrance.

30. **Pull-through pavement markings associated with left-side ramps.** The Atlanta bus crash in 2006 suggested that both pull-through signing and pavement markings delineating the main travel way are critical to keep motorists attuned. Yet the pavement striping guidance has lagged behind. Use of pictograms (route shields) has not been explored for managed lanes, but it is common for mainlanes. The likelihood of having left-side local access ramps being confused with the main travel way is most common on managed lanes. This represents a safety issue that needs further research and guidance given the number of high-speed and low-speed left-side access ramps in operation and in development.

31. **Toll rate signage.** There are two main categories of possible consideration provided for this research idea: continuous-access conditions and multisegment corridors. The list below describes key concepts for each.
    - Continuous-access conditions:

    - Minimum spacing.
    - Optimal placement.
- Multisegment corridors:
    - Destination pricing vs. next-segment pricing.
    - What to sign and for where.
    - Accounting standards.
    - Maximum multisegment trip pricing vs. performance management.

32. **HOV symbol usage.** The current MUTCD (*42*) dictates that the general HOV diamond symbol should not be used for priced managed lanes. Many current managed lane systems utilize the diamond HOV symbol on fixed and changeable message signs to convey that there are times that HOVs receive a discount. It is not clear if motorists understand this subtle distinction. This is further complicated by managed lane strategies that feature variable occupancy requirements based on schedule or demand. For instance, an HOV3+ may be free, but an HOV2+ would pay a toll.

33. **Provision of comparative travel time information**. The MUTCD (*42*) does provide an example of a comparative travel time sign in Figure 2G-20. Many agencies resist providing this information for fear that it will be seen as a guaranteed time. A reasonable compromise seems to be indicating the travel time (or speed, which may be more informative to unfamiliar drivers) in the general-purpose lanes. This information, coupled with the toll cost, provides a good, if not completely perfect, basis for decision without jeopardizing the good will of toll-paying customers when the managed lanes are not running as well as expected. One of the main benefits of managed lanes is improved reliability of travel time, and the provision of a point prediction for travel time may undermine this message. SHRP2 Project L14 provided a lexicon for disseminating travel time reliability information to users and may serve as a resource for this line of research.

34. **Communication on managed lane network connections.** As managed lanes expand in metropolitan areas, more connections are being made among the different facilities. In many areas, it is possible that these interconnected facilities have different operating rules because they are operated by different agencies or have different management goals. It is unknown how best to communicate to drivers the availability and status of these networks. In 2016, the Texas Department of Transportation will be sponsoring a research project on this topic, which may serve as a resource for this line of research.

35. **Pylon design.** While the use of pylons to distinguish preferential lanes has been evidenced since the first projects were first implemented in 1970, the application of these devices has accelerated as tolling has been adopted on managed lanes. Through the years, there has been a wide range of pylon designs tested and deployed from a variety of manufacturers. Currently, there does not appear to be a standard pylon design, and options for various applications in high-speed traffic conditions are not available from research or guidance literature. Yet there appears to be extensive experience in pylons among a number of states, particularly for applications involving

permanent placement on different pavements. The life cycle of pylons represents one of the highest maintenance cost categories for project operations, and the safety implications of dislodged pylon products is not understood. The expanded use of pylons is anticipated on projects currently being implemented. More information and testing on the performance and application of pylons are needed to support the expanded use of this device.

IMPLEMENTATION AND DEPLOYMENT

36. **Political/public opinion.** Most marketing and outreach guidance is oriented toward project concept development. However, contemporary experience shows that political support for managed lanes often breaks down during implementation and shortly after deployment. New guidance is needed on how to manage public opinion and provide valued information during initial project challenges. Required components would include optimal types of engagement at various points of development; education and messaging; tools; visual, audio, and static messaging; and strategic marketing.

37. **Network communication specifications.** Priced managed lanes require highly responsive, accurate, and sustainable systems for communications. Transactions, violations, traffic monitoring, and pricing information must all be communicated in real time. As such, more information is needed about appropriate specifications for data transmission speeds and bandwidth, network redundancy, agreements for sharing conduit, and acceptable wireless solutions.

38. **Benefit-cost analysis.** Priced managed lanes have different calculations of benefit and impact than general-purpose lanes. As a result, additional guidance for how to conduct a benefit-cost analysis for a priced managed lane project is needed. While specifics of that analysis will vary based on the project (particularly for tolled versus non-tolled projects), a resource that describes the steps and the data needed to conduct a thorough economic analysis will be valuable to many road agencies and investment partners.

OPERATIONS AND MAINTENANCE

39. **Incident and emergency procedures.** Several types of incidents impact managed lanes: major incidents, including natural or manmade disasters, weather, and multivehicle collisions; and minor incidents. Given the highly constrained design settings of many projects, not only major incidents but also minor incidents require a greater level of roadway monitoring with commensurate investments in intelligent transportation systems and response planning. How these effects translate into special coordination with first responders, suspension of eligibility and/or toll collection, and facility closure are all topics that should be explored for greater agency guidance.

40. **Accuracy requirements for toll collection**. As priced managed lanes collect tolls from customers, and by association carry a monetary handling requirement, the accuracy of the transaction is essential to the operation of the facility. As agencies incorporate license plate recognition systems, new questions have emerged regarding

various systems and their accuracy. Topics to be explored include roles for human-based review, acceptable occlusions or exclusions (e.g., missing or bent plates, partial plates, etc.) that still permit a positive identification, confidence-level guidance, variability in read accuracy by weather condition, color or near-infrared spectrums, and alternatives to license plate identification.

41. **Occupancy enforcement best practices.** Sponsor agencies have identified multiple means of accommodating occupancy requirements for the use of managed lanes (priced and non-priced). Different declaration options are available; however, the effectiveness of declaration options, automated systems, and visible police presence on occupancy violations is largely unknown. A scientific study of violations on managed lanes with differing enforcement mechanisms would provide sponsor agencies with more definitive guidance about what works best for occupancy enforcement. This may include an inventory of violations by various managed lane designs, identification of costs and collection, and issues for considering the use of automated systems.

42. **Customer service and back-office requirements**. Sponsor agencies for priced managed lanes currently lack guidance for specifying contractor requirements for customer service center and toll back-office operations. Additional guidance is necessary in order to provide consistency in experience, cost comparability, and service competitiveness. Topics could include guidance for customer communication systems, key performance indicators for customer interaction, data security and privacy, in-field vs. remote operations, invoicing standards, and account management.

CHAPTER 7

SUMMARY

BASIS FOR RESEARCH

The sheer number and complexity of the roadway design considerations that are part of the development of a managed lane system have increased. The variations in separation, access, tolling, project financing, and other factors point to a change in how managed lane facilities are designed, evaluated, and implemented. The objective of NCHRP 15-49 was to develop implementation guidelines for the planning, design, implementation, operations, and maintenance of managed lanes. The final product—*NCHRP Research Report 835*: *Guidelines for Implementing Managed Lanes* (*1*)—will become the primary reference on managed lanes and complement other national guidelines. It was designed to be applicable to practitioners at all levels of experience with managed lanes and to be used to support informed decision-making. The scope of this project was limited to managed lanes on freeways and expressways.

REVIEW OF LITERATURE AND EXISTING GUIDANCE

There are in existence a number of references that serve as manuals or guidelines and have material relevant to managed lane planning, design, implementation, operations, or maintenance. As part of Task 1 efforts on NCHRP Project 15-49, the research team conducted a review of literature on these topics; over 160 sources were reviewed for this task, and those sources are summarized in Appendix A of this report.

As part of Task 2 efforts, the research team conducted a review of current policies, guidelines, and other documents in use by agencies that operate managed lanes. Rather than attempting to review documents from every agency in the United States, the research team reviewed 36 online documents from 16 state, regional, and local agencies considered to be among the leaders and innovators in managed lanes. The information from those documents is summarized by topic in Appendix B of this report.

STATE OF PRACTICE

In a parallel effort on Task 2, the research team members contacted managed lane practitioners in two ways to explore priority gaps in understanding and guidance for the development of new managed lanes. The research team conducted one-on-one stakeholder interviews in January and February of 2014. A total of 18 state departments of transportation and regional operating agencies were contacted to conduct one-on-one interviews by phone, with 11 successfully completed. Researchers also conducted a group survey with the TRB Managed Lanes Committee (AHB35) in January 2014, concurrent with the TRB Annual Meeting in Washington, DC. Details of the methodologies used and the results obtained in those efforts can be found in Appendix C of this report.

PHASE II STUDIES

Based on the findings from Tasks 1 and 2, the research team developed a work plan for Phase II of the project with input from the project advisory panel. The work plan included a series of studies on existing practices and operations, which were accomplished by contacting practitioners for in-depth details on their current and planned facilities in addition to collecting and analyzing field data from managed lanes across the country. Specifically, the researchers developed case studies on current decision-making practices, investigated the effects of selected design dimensions within the managed lane envelope, explored the characteristics of operating speed on managed lanes, and documented current practices related to managed lane access. A summary of each of those studies is provided in the following sections.

Case Studies

The objective of this study was to gain an understanding of how design decisions are being made on managed lane projects by agency sponsors. While design basics are often documented in project descriptions, the basis for how the design came to be and what factors influenced the design and design process are often missing. This research examined designs for existing operational projects and for those in design, under construction, or soon to open at the time of the study. It documented current implementation approaches by providing an understanding of the design and answers to why and how certain design decisions were made, including documentation of the design options that were considered and rejected.

Design decision-making was defined in this study as the process from conceptual development during planning through implementation and operation when design modifications may have been made after the project opened. This documentation provides insights into the primary influences that appear to be affecting the project development process and project design, which, based on representative case studies, is not always linear and straightforward. These experiences, while not expansive enough to form a basis for best or preferred practices, helped to confirm the range of practice and the factors commonly influencing design decisions.

Practitioners from six metropolitan regions (Atlanta, San Francisco–Oakland–San Jose Bay Area, Dallas–Ft. Worth, Los Angeles, San Diego, and Seattle) were contacted for information on their facilities and the reasoning behind some of the design decisions that were made in constructing them. Practitioners had close knowledge of or were instrumental in the decision-making process for their respective projects and agencies. Efforts were made to obtain information from the practitioner who was charged with these decisions at the time they occurred, even if the individual had moved on to other roles or employers.

An expansive list of questions forming a discussion script was developed for practitioner meetings. The basis for questions was to capture both the process that agencies went through in responding to their specific project goals and objectives and in documenting the rationale behind design selection including influencing factors. Practitioner meetings were conducted singly and in groups through teleconferences. Some responses to questions were also provided

in writing from practitioners preceding or following the meetings. The list of questions comprising the interview script is included in Appendix D, and the findings from the practitioners' responses to those questions were grouped into regional case studies (see Appendix E).

Details of the study can be found in Chapter 2 of this report. The two primary categories of information are project conversions (i.e., tolling-based improvements implemented on HOV lanes) and new construction. The chapter provides comparative characteristics of facilities that the practitioners were responsible for designing; a summary of challenges the practitioners faced; a description of organizational and procedural practices in design; and listings of key transferable practices, identified gaps in practice, and lessons learned.

Dimensions Within Managed Lane Envelopes

This research project included two studies on the trade-offs and effects of lane, shoulder, and buffer widths on managed lane facilities. Study 5R.3 gathered managed lane practitioner information on the trade-offs considered when making cross-section width decisions and reviewed this information using focus groups. Study 5R.2 identified the relationship as revealed through travel data between operations and cross-section width, including the type of buffer design separating the managed lanes from the general-purpose lanes. Key measures believed to be affected by lane, shoulder, and buffer widths are operating speed and lateral position because drivers may adjust their speed or position in the managed lane depending on their proximity to a concrete barrier or adjacent general-purpose lane.

The objectives of Study 5R.2 were to collect speed and lateral position data on existing managed lane facilities with a range of lane widths, shoulder widths, and buffer widths within both tangent and horizontal curves and identify potential relationships between the geometric design element values and the measures of effectiveness.

The objective of Study 5R.3 was to gain an understanding of how design trade-off decisions and prioritization are being made by practitioners on managed lane projects. Through this effort, the research team determined the priorities of managed lane practitioners in making decisions on lane width, shoulder width, and buffer width.

The findings from both studies were used to develop updated guidance to help practitioners determine a priority order of adjustments. The list of adjustments was developed based on observations and practical considerations. The research approach was divided into the following activities:

- Compilation of existing practices.
- Survey of applied methods by practitioners.
- Observation and documentation of current conditions.
- Discussion groups with practitioners.
- Application of field and focus group data along with findings from the literature to current practice.

A relatively consistent approach between agencies to reducing lane, shoulder, and buffer widths in less-than-ideal cross-sections shows an important exchange of information between transportation agencies to the significant benefit of the traveling public, but areas for improvement were identified in the review of existing guidelines. The practitioner focus groups also identified factors not mentioned in current guidance and other issues related to cross-section widths. The findings from the safety literature were clear in that reduction in left shoulder width is associated with increased number of crashes; safety studies for general-purpose freeway lanes also have found that reduction in lane width is associated with more crashes. Statistical analysis of the data from the field studies found five variables that affect lateral position of vehicles within a managed lane:

- Vehicle type—Larger vehicles, such as buses, are closer to the shoulder edgeline, while smaller vehicles, such as motorcycles, are a greater distance away.
- Presence of a vehicle in the neighboring general-purpose lane—Vehicles being present in the general-purpose lane results in the managed lane vehicle shifting closer to the shoulder edgeline.
- Pylons—Managed lane drivers shift away from the pylons placed in the buffer.
- Horizontal alignment (tangent or curve) and the direction of the horizontal curve (left or right).
- Left shoulder, lane, and buffer width—The best statistical model used a parabolic curve to model the relationships, resulting in smaller values for those elements having greater influence on the lateral position. For example, modifying a 6.5-ft shoulder to a minimum shoulder (i.e., 1.5 ft) will result in drivers moving to the right about 0.5 ft; however, if an 18.5-ft shoulder is reduced by 5 ft, the impact in operations is negligible (drivers will shift only about 0.11 ft toward the right).

Details of the activities and findings from these studies are provided in Chapter 3 of this report. Key findings include the following:

- The maintenance of adequate shoulder width is desirable.
- The practice of reducing the lane width by 1 ft (from 12 ft to 11 ft) and providing that foot of width to the buffer is appropriate.
- Drivers shy away from the concrete median barrier. Research findings indicate that lateral position is highly affected for narrow shoulder widths.
- The use of pylons affects lateral position. Using the pylons within a wider buffer can offset the impacts on lateral position.
- As expected, driver's lateral position is affected by horizontal curvature.
- The impact on lateral position is greater within the minimal values for shoulder, lane, and buffer widths. For example, a 1-ft reduction in shoulder width results in greater changes in lateral position when the shoulder width is near minimal values (e.g., 2 or 4 ft) as compared to when the shoulder width is near desirable (e.g., 8 ft or 14 ft).
- Research findings from recent safety research indicate that—in general—the left shoulder width should be reduced before the general-purpose lane right shoulder width. Safety research also indicates that it is better to reduce a shoulder width by 1 ft prior to reducing a lane width by 1 ft; however, it could be different depending on site conditions. Tools, such as the *Highway Safety Manual* (*14*) and associated spreadsheet or the equation (and spreadsheet) developed as part of a recent TxDOT project (*16*), are available to help predict crashes for freeway segments, and these

tools should be used to evaluate the trade-offs for different freeway general-purpose lane cross-section decisions.

- Practitioners would like to have a step-by-step process like what is currently included in the AASHTO HOV guide (*3*); however, recent findings from safety research indicate that any reduction in freeway shoulder or lane width is associated with increased crashes. For general-purpose lanes, a 1-ft reduction in lane width is associated with greater increase in crashes than a comparable 1-ft reduction in shoulder width; however, rarely is a cross-section decision just a decision about a single foot. Trade-offs between different cross-section options need to be evaluated to determine the optimal design.

Based on the findings from the two studies, the following changes to practice can be considered:

- Regarding the practice of reallocating a portion of the lane width to the buffer width, reducing the lane width by 1 ft (from 12 ft to 11 ft) and increasing the buffer width by the same amount is appropriate.
- Drivers shy away from the concrete barrier. The use of minimal width for the left shoulder results in managed lane drivers being closer to the general-purpose vehicles. A buffer can offset this impact.
- Consider providing additional buffer or shoulder widths within horizontal curves since drivers are shifting their lateral positions when driving on a horizontal curve, especially horizontal curves to the left.
- Consider the buffer width when using pylons. Drivers shift away from the pylons, and a wider buffer can be used to offset this behavior.
- If insufficient space is available for a full-width left shoulder, consider splitting the available width between the left shoulder and a buffer. Managed lane vehicles are closer to the center of the lane when these values are similar.

Operating Speed on a Buffer-Separated Managed Lane

Speed data from Los Angeles and Orange County, California, and Dallas, Texas, were used to investigate the variables that affect operating speed in buffer-separated managed lanes. The dataset represented over 130 unique sites. The evaluation focused on daytime, weekday operations and was subdivided to better investigate if different general-purpose lane variables are influential during congested and uncongested conditions. Congestion was defined as traffic flowing with a density greater than 25 vphpl.

When the managed lane was uncongested, the model results always had an intercept value over 50 mph, reflecting the high speeds in the managed lane under favorable conditions. All scenarios showed that the managed lane volume and the speed in the general-purpose lanes were related to the speed in the managed lane (statistically significant).

The Dallas analysis, which used speeds averaged by one-minute increments, showed that the factor with the most influence on uncongested managed lane speed was the managed lane geometry. The managed lane envelope (sum of left shoulder width, managed lane width, and buffer width) was found statistically significant in explaining variability in managed lane

speed. For each additional foot over 16 ft of envelope width, managed lane speed increased by approximately 3.2 mph. The influence of volume in the managed lane was also found to be statistically significant; however, its influence was nominal when the managed lane was uncongested. Managed lane speed increased at a greater rate in response to the general-purpose lane speed when pylons were present. Speeds on the managed lane increased by 0.03 mph (flush buffer) or by 0.12 mph (pylons in buffer) for each 1-mph increase on the general-purpose lane when the general-purpose lane was congested.

In contrast, the California analysis, which used speeds averaged by one-hour increments, showed that the variable with the most influence was the volume in the managed lane. This analysis also found a relationship between speed on the general-purpose lane and speed on the managed lane. Speeds on the managed lane increased by about 0.24 mph for each 1-mph increase on the general-purpose lane.

Similar to a previous study, this evaluation also found a significant difference in operating speed by day of the week. Drivers in Dallas were faster on Friday as compared to Wednesday (about 0.38 to 0.58 mph), and drivers in Los Angeles/Orange County were faster on Monday or Friday as compared to Tuesday through Thursday (about 0.40 mph).

Congestion on the managed lane was also examined with the California data. The speeds in the general-purpose lanes along with managed lane volume had the greatest effect on managed lane speed—rather than the managed lane geometric dimensions—when the managed lane was operating under congestion. This analysis found that managed speeds were slowest on Friday as compared to the other days (between 1.1 and 3.7 mph) when the managed lane was congested.

A possible explanation for the lack of a managed lane speed relationship with managed lane geometry in California may be found in the way the data were collected. Because the California speeds were in one-hour increments, the effect of averaging the speed over a larger time period (compared to the one-minute increments in Dallas) may be masking the effects of geometry on speed. A per-minute speed may help to illustrate the effects of geometry because it is more sensitive to the presence of vehicles in the adjacent general-purpose lane, while a per-hour speed would likely obscure those effects, making geometry an insignificant variable when compared to volume and other factors. Another factor could be that for Dallas, the speed of the general-purpose lane adjacent to the managed lane was observed, whereas in California, the speed data for general-purpose traffic were the average of the speed from all general-purpose lanes.

Access

The study on managed lane access had two information-gathering efforts: a survey of recent practice by practitioners, and a compilation of existing policies. The objective of this study—Study 5R.4—was to answer the following questions and topics for practitioners to evaluate access as part of planning, design, and implementation activities:

- What are appropriate ways to evaluate and consider impacts of restricted and continuous at-grade access?

- What level of operational analysis is needed during the planning phase to determine operational feasibility?
- What are appropriate criteria for determining ingress/egress locations and impacts on pricing demand?
- What are preferred approaches to at-grade access for different levels of demand associated with single- and multilane concurrent-flow treatments?

An email and telephone survey of selected managed lane practitioners was conducted to identify existing practices and decision-making procedures as they pertain to the design of managed lane access. The intent of the survey was to follow up on the interviews conducted in Study 5R.1, with a focus on access characteristics and the decisions associated with them, to answer the questions described in the study objective. The primary source of information was drawn from practitioners who had close knowledge of or were instrumental in the decision-making process for the design or implementation of access to managed lanes. Eight practitioners from six states were invited to participate, representing experience with access on 10 managed lane facilities. Six of the eight practitioners responded, providing information about nine existing facilities, including two that have planned changes to their access.

The practitioners participating in this study use a variety of tools and guidelines, both regional and national, and indications are that their facilities operate acceptably. However, there was a consistent message from the respondents that they would like to be better informed on practices in other jurisdictions, to see what options they had not previously considered or take advantage of lessons learned on prior projects to improve their confidence that the access they have provided is the most appropriate for the facility. In particular, there are questions about sufficient weaving distances between managed lane access and general-purpose access, as well as appropriate lengths of weaving zones for shared ingress/egress. Guidance on how to determine what factors should be considered when locating and designing access would also be beneficial because there are many potential (and potentially competing) factors that could be used in the decision; while there may not be a single right answer, agencies should be able to consider what factors (e.g., operations, safety, revenue) are most appropriate for a given facility and then prioritize the factors most important to them.

The number of documents containing written guidelines or policies for the design of managed lane access has increased in recent years, but much of the information found in those documents seems to be based on earlier guidelines dating back a decade or more. In some cases, states have conducted studies to help inform them on a particular topic for their region, but results from national research to help populate existing and future guidance did not appear to be widely available. Rather, information from the earlier guidelines can be found in many of the later documents. This provides consistency in design for a selection of key design features, but it does not provide many details on the underlying basis for those design guidelines. As a result, practitioners tend to rely on their own experiences for engineering judgment to make decisions on site-specific applications not found in existing guidelines. Practitioners in this study stated a desire to have more guidelines available to inform their decisions, and these guidelines would be based on practices of other practitioners who have shared their experiences and the outcomes of their decisions. Details of the study on managed

lane access, including key findings from the practitioner interviews, can be found in Chapter 5 of this report.

KNOWLEDGE GAPS

Based on the information compiled in the previous tasks, the research team identified gaps in existing knowledge that could be explored through additional research. In some cases, these identified gaps are related to subject matter, where limited documentation of prevailing practice exists. In other cases, gaps are related to the lack of syntheses that pull together the wealth of commonly available information so that the practitioner can more easily understand what practices are prevalent and why. Researchers documented over 40 knowledge gaps and potential research ideas, which are categorized and presented in Chapter 6 to correspond with chapters in the guidelines document.

APPENDIX A

LITERATURE REVIEW

INTRODUCTION

Existing Key Reference Documents

As part of the Task 1 efforts on NCHRP Project 15-49, the research team conducted a review of literature on the planning, design, implementation, and maintenance considerations of managed lanes. There are in existence a number of references that serve as manuals or guidelines and have material relevant to managed lane planning, design, implementation, operations, or maintenance (see Table 42). In many cases, these documents have information or guidance that could be referenced for multiple topics within the anticipated outline for the guidelines document that will be produced in this project. Because these sources are well known, they were not part of this review. A summary of those documents is provided here for completeness.

Table 42. List of key reference documents on managed lanes or HOV lanes.

Reference	Num
AASHTO *A Policy on Geometric Design of Highways and Streets* (the *Green Book*) (2011)	*7*
AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (2004)	*3*
AASHTO *Guide for the Design of Park-and-Ride Facilities* (1992)	*43*
Caltrans *HOV Guidelines* (2003)	*5*
FHWA *A Guide for HOT Lane Development* (2003)	*44*
FHWA *Freeway Management and Operations Handbook* (2011), also known as FMOH	*45*
FHWA *Manual on Uniform Traffic Control Devices* (2009)	*42*
FHWA *Priced Managed Lane Guide* (2013)	*36*
FHWA *Freeway Geometric Design for Active Traffic Management in Europe* (2011)	*46*
NCHRP Report 414: *HOV Systems Manual* (1998)	*38*
NCHRP Report 694: *Evaluation and Performance Measurement of Congestion Pricing Projects* (2011)	*47*
NCHRP Web-Only Document 191: *Analysis of Managed Lanes on Freeway Facilities* (2012)	*39*
TCRP Report 95: *Traveler Response to Transportation System Changes Handbook, Chapter 2: HOV Facilities* (2006)	*48*
TxDOT *Managed Lanes Handbook* (2005)	*30*

FHWA Manual on Uniform Traffic Control Devices (2009)

FHWA's *Manual on Uniform Traffic Control Devices* 2009 edition (*42*) was the first edition to include any mention of managed lanes related to tolling. Prior editions dating from 1976 had some guidance and standards for signs, markings, and signals for preferential use or restricted lanes (e.g., HOV or bus lanes). Prior to this, the 2006 Texas MUTCD (*49*) and Caltrans HOV guidelines (*5*) included sections for toll and managed lane guide and regulatory signs and in the case of the Texas reference, a definition of HOT lanes. Caltrans provided in-depth sign and pavement marking guidance for HOV lanes that went into more detail than the

federal MUTCD. The federal MUTCD material was developed by headquarters staff with input from the Toll and Managed Lane Task Force of the National Committee on Uniform Traffic Control Devices (NCUTCD), an advisory group comprised of practitioners and researchers. Because of the public notice requirements for new editions of the MUTCD, the material in it was produced between 2005 and 2008 and reflects operational strategies in place at the time, and it attempts to capture likely signing applications looking forward at that time. During this same period, many more tolled managed lane systems were coming online and, in the absence of any guidance in the MUTCD, agencies had to develop their own traffic control device schemes, which later proved to be noncompliant with the 2009 edition.

The two main chapters in the 2009 MUTCD are "2F Toll Road Signs" and "2G Preferential and Managed Lane Signs" with some mention in the pavement markings and signals chapters of issues pertaining to managed lanes. The most controversial standard introduced in the 2009 MUTCD was the establishment of purple as a unique color to designate lanes that require a preregistered form of electronic payment (i.e., an ETC tag). At the time, license plate recognition systems and related billing procedures were just emerging, and the 2009 manual does not address these systems in any depth. Many operators objected to the new standards that treated ETC facilities with different-looking signs than those that allowed pay-by-plate systems or those that allowed HOV discounts.

Many other operational and technological challenges and changes have occurred since the MUTCD material was created. These include:

- Dynamic pricing is only addressed with guidance relating to distance-based pricing, with no discussion of variable pricing based on vehicle type or occupancy.
- Pricing schemes can be based on road segments or by distance. The regulatory signs to post these different pricing schemes are not defined in the MUTCD.
- Switchable toll tags, which allow users to self-declare their occupancy status when entering the lane in order to be billed properly, did not exist in 2009. Anecdotal reports from the Capital Beltway opening suggest there is user confusion about eligible tags, and experiences are just now coming in from switchable tag applications in California.
- Regulatory signs explaining ETC requirements, hours of operation, and prohibited vehicles are presented in piecemeal fashion and do not represent the sign sequences required to convey all the regulatory information.
- Dynamic lane assignment arrows are becoming more common in the United States.
- Variable speed limits are addressed only in the context of local roads and driver feedback signs used in work zones and school areas.
- Dynamic pavement markings through LED-raised pavement markers are not addressed.
- Shoulder running operations are not addressed, and there are important regulatory sign and pavement marking issues both in language and placement of devices. Washington State DOT is the only state to offer HOV shoulder running pavement marking guidance dating from the early 1990s in earlier editions of its design manual.
- Exit numbering policies in the managed lane are not clear. Using the same exit numbers as the mainlanes may cause confusion to drivers when they see a sign for a managed lane exit that must occur upstream of the mainlane exit to allow time for the

managed lane driver to exit the managed lane and weave over. For consistency with maps and navigation systems, however, using the same exit numbers is preferred. New York State used exit numbering as a primary means for such information when it opened HOV lanes on I-495 in the late 1990s, but it has no published guidance for this practice.

- The use of interchange sequence signs, where upcoming exits and their distance are provided, is highly recommended. Previous research conducted by Dr. Chrysler in this area has shown that the main reason drivers are reluctant to use a managed lane is that they are unsure about the destinations served (*147*).
- Issues of how to use traffic control devices to reduce driver expectation violations due to access point design are not addressed.
- Managed lane access to a major interchange is not addressed. For instance, in the Capital Beltway, there is no direct access to the Chain Bridge Road interchange, a major feeder to the central business district. Users who wish to reach that destination may choose not to use the managed lane if they know that ahead of time.
- Directional legs of major roads are not served.
- When there are restricted unidirectional access points, some locations provide access **to** the managed lane, but not an exit **from** the managed lane.

Research has not kept pace with the expanding and evolving development of managed lanes. FHWA has sponsored some studies of dynamic lane assignment signs (*50*, *51*, *52*), but the other items on the list above have not been studied in any depth, particularly from a human factor perspective. Poor signing can cause drivers to make late decisions and pose safety problems. During the recent opening of the Capital Beltway Express Lanes, the local news was filled with images of cars backing up to get out of the express lanes after making a late decision.

TxDOT Managed Lanes Handbook, Technical Report 0-4160-24, October 2005

The *Managed Lanes Handbook* (*30*) was developed for TxDOT to help the agency make informed planning, design, and operational decisions when considering managed lanes within Texas. The document presents the critical findings obtained over five years of research between 2000 and 2005, covering a broad range of topics. The handbook provided some of the early foundational guidance for HOV-to-HOT conversions and added managed lanes and still provides relevancy in much of the guidance, but it currently has a number of limitations:

- At the time the research was initiated, there were only four projects in operation: two in California and two in Texas.
- Federal enabling legislation has changed since the handbook was published.
- The fundamental driver decision models and principles presented in the handbook are still relevant, but the traffic control device guidance has been superseded by the 2009 MUTCD update.
- Enforcement strategies have expanded significantly beyond those presented in the handbook with the introduction of carpool registration systems and updated transponder technologies.
- The operations discussion is limited, particularly as it relates to the development of a comprehensive project concept of operations.

AASHTO A Policy on Geometric Design of Highways and Streets (2011)

The AASHTO *A Policy on Geometric Design of Highways and Streets* (*7*) is commonly known as the *Green Book*. The document is the key reference for roadway geometric design. It "provides guidance based on established practices that are supplemented by recent research." Information is provided for design controls and criteria (vehicles, drivers, pedestrians, etc.), cross-section elements (e.g., shoulders or drainage), and key design elements such as stopping sight distance or horizontal and vertical alignment. Information is also provided within chapters organized by functional class. The chapters on freeways (Chapter 8) and grade separations and interchanges (Chapter 10) contain material relevant to managed lane design.

Within the freeway chapter is Section 8.4.8, which is on accommodation of managed lanes and transit facilities. Managed lanes are defined as "highway facilities or a set of lanes where operational strategies are implemented and managed in response to changing conditions to increase freeway efficiency, maximize capacity, managed demand, and generate revenue. This definition matches the FHWA definition on their website addressing managed lanes. Examples of managed lanes include high-occupancy vehicle lanes, value-priced lanes, high-occupancy toll (HOT) lanes, and exclusive or special-use lanes such as express lanes, bus lanes, transit lanes, and reversible flow lanes" (used by permission). The *Green Book* provides two references for additional information: a 2004 report entitled *Managed Lanes: A Cross-Cutting Study* (*53*) and the 2003 version of the FHWA *Freeway Management and Operations Handbook* (*45*). Most of Section 8.4.8 is devoted to transit, with several figures showing how to incorporate bus stops at the freeway level. The grade separations and interchanges chapter does not discuss ramp design for managed lanes.

Currently, the *Green Book* is comprehensive in addressing design issues, with over 800 pages. The AASHTO task force responsible for the document recognizes that the document is very large. Adding the breadth and depth of information needed to cover the issues related to managed lanes is beyond the document's capacity. A unique document dedicated to managed lane design—as is the objective of this NCHRP 15-49 project—is in line with the goals of the AASHTO task force.

FHWA Priced Managed Lane Guide (2013)

The *FHWA Priced Managed Lane Guide* (*36*) was completed in late 2012. The guide is intended to be a comprehensive source of collective experience gained from priced managed lanes implemented in the United States through 2012. The guide presents a wide range of information on priced managed lanes. The purpose of this guide is to assist transportation professionals as they consider, plan, and implement priced managed lane projects.

The *Priced Managed Lane Guide* also updates FHWA's 2003 *Guide for HOT Lane Development* (*44*). At the time the earlier guide was written, there were only four priced managed lane facilities operating in the United States, and few transportation professionals had firsthand experience with these facilities. As of May 2012, there were 14 operating managed lane facilities nationwide, with an additional 14 in construction, and approximately

25 others in planning. (As of November 2013, there are now 19 such projects in operation in nine states.)

The guide addresses a wide range of policy, outreach, and technical issues associated with the implementation of priced managed lanes, focusing on the knowledge and experience gained from the new projects that have advanced in the past decade. The guide also provides detailed profiles of 21 priced managed lane projects that are either operational or nearing completion. These resources represent the most comprehensive compilation of data and information prepared by FHWA on priced managed lanes to date.

The guide benefited from the ongoing input and technical review of a peer development group of over 30 transportation professionals around the country who are involved in implementing or operating priced managed lane facilities. While the guide provides the most current and comprehensive synthesis of current managed lane practice, it does not provide definitive guidance on facility design, access, or separation treatments backed by rigorous research on facility performance and safety.

AASHTO Guide for High-Occupancy Vehicle (HOV) Facilities (2004)

A more comprehensive version of the *NCHRP Report 414: HOV Systems Manual* (*38*) was the AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*) published in 2004. This resource delves more thoroughly into design and operation issues, and benefits from almost double the number of project experience that existed when NCHRP Report 414 was authored. It also covers HOV planning, implementation, operation, and design on both freeways and arterials. By 2004, many sketch planning techniques had been researched and applied, so the practitioner was given much better guidance in successfully implementing projects. Priority lane pricing was mentioned for the first time, even though there were only a few such projects in operation employing ETC. An expanded number of issues were addressed that formulated wider potential application and implementation strategies including commercial truck lanes and lane conversions. To make the guide easier for practitioners, major types of designs are separately presented alongside commensurate access, enforcement, signing, and pavement marking provisions.

The timing of this guide did not permit a detailed discussion of pricing strategies that were just emerging. Many versions of signing and pavement markings were applied to similar projects, and the guide did not prescribe a best practice among common designs and operations. Some topics were ahead of their time and did not represent any or few on-the-ground examples, such as truck lanes and general-purpose lane conversions to HOV. Linkages with emerging ITS applications, particularly ATM, are missing or were not yet fully exemplified. System-wide issues such as access connections were not addressed since few places had HOV systems.

The guide was based on the best practitioner experience at the time, and most accepted standards of practice were covered. However, no research was conducted on design or operation issues; the majority of the guide borrowed heavily from other relevant and recent resources including NCHRP Report 414 and various state DOT input. However, in 2004 there

were only a handful of pricing projects in operation. Case studies now available from UPA/CRD priced managed lane projects would have greatly aided this effort in better documenting expected benefits in performance because operational data were largely lacking or unavailable when this document was prepared.

FHWA Freeway Management and Operations Handbook (2011)

The *Freeway Management and Operations Handbook* (*45*) provides an overview of managed lanes as a component of freeway management activities. It provides context for considering managed lanes as a subsystem in relation to other management and operational treatments for freeways and specifies strategies for either dedicated lane or all lane management. In addition, it identifies operational and design considerations pertaining to implementation and describes various managed lane strategies and technologies, special issues in design and implementation, and complementary actions for improving effectiveness.

The initial version of the *Freeway Management and Operations Handbook* was published in 2003. The 2003 version included separate chapters for HOV lanes and managed lanes. At the time, tolled managed lanes had only limited operational experience on four facilities. In 2009, a revision to the chapters on HOV lanes and managed lanes was commissioned, with the charge to consolidate the chapters into one and leverage the lessons learned from all HOV lanes with the eight tolled facilities, which had opened in the intervening time.

The document's intended purpose is an articulation of current practice as it pertains to freeway managed lane operations. No primary research was conducted; design, operations, and implementation issues unresolved from previous efforts remained unresolved. The chapter did not fully incorporate changes in the 2009 MUTCD, which were being drafted in parallel and not published. Needed research includes:

- Impacts of tolling on freeway operations, including subsystem separation and integration requirements between toll collection, traffic information, and traveler communication.
- Impacts of toll system requirements on freeway operations.
- Potential integration of tolling system infrastructure with other freeway management systems (i.e., ATM, ITS, ramp metering, etc.).
- Operational policy implications related to managing speed differentials, monitoring and responding to incidents in either roadway, performing maintenance, and developing enforcement best practices.
- Determination of flexibility in subsystem specifications.

An effort to update the entire document is underway by a consultant of FHWA, and outreach is occurring to examine a new handbook structure as well as identify gaps and updated needs for subject areas.

Caltrans HOV Guidelines (2003)

Having one of the largest legacy freeway HOV systems implemented by any state, Caltrans has authored several guidance treatises dating from 1991. One of the first HOV projects to

open in the United States was the El Monte Busway in the early 1970s, and many more projects followed. These guidelines helped bracket parallel operational and design experiences in both northern and southern California, accommodating consistency in how HOV lanes were planned and implemented. All types of HOV lane designs and operations were represented, with greatest emphasis on concurrent-flow lanes that represent the majority of freeway facilities found in the state. The 1991 guide was more of an orientation to HOV lanes with guidance provided for design and operational trade-offs. Subsequent editions provided ever greater levels of specificity, including signing and pavement marking templates that helped achieve regional consistency in ever-expanding HOV lane systems. More recently, policy directives have been issued as interim updated guidance affecting such topics as access options and design treatments until such time that a new comprehensive guide is drafted and adopted.

The 2003 Caltrans guidance (*5*) is the most extensive of any state, and the legacy of guidelines through the decades tracks extensive operational experience and in-state supported research into such topics as ingress/egress, enforcement best practices, and performance. However, even with the first two ETC examples being in California (SR 91 and I-15), tolling on managed lanes has not received widespread expansion and interest until recently with the openings of I-680, SR 237/880, I-10, and I-110 projects. Accordingly, Caltrans guidelines are just now tackling the policy, operation, and design issues commonly being experienced nationally on express lanes into a new guidance effort.

The guidelines and policy directives offer insightful perspectives on the largest basis for managed lane operation. However, research is needed to support a wide range of topics being confronted in the state as an adopted system of express lanes emerges in San Diego and the Bay Area and is being studied among the various counties in the Los Angeles area. Notable issues include access treatment and design, separation and buffer treatments, system-level connections, accommodation for dual lanes, transitions from HOV to tolled lanes (and the commensurate impacts to general-purpose traffic), degradation on existing HOV lanes (and how to go about raising occupancies from 2+ to 3+), enforcement needs and best practices, incident management, cost, revenue and maintenance sharing for express lanes, planning and implementation, and a wide range of policy and delivery issues due to the large number of agencies in California that have a role in planning and implementing these facilities

FHWA Guide for HOT Lane Development (2003)

Published in 2003, *A Guide for HOT Lane Development* (*44*) provides FHWA's guidance for the implementation of HOT lanes based on the experience emanating from the nation's first four operating HOT facilities. The document is intended to assist transportation professionals contemplating HOT lane projects, and focuses on how the implementation of these facilities differs from those associated with more traditional highway improvements. The guide presents different organizational frameworks for HOT lane projects, discusses the need for effective public outreach and consensus-building efforts, and provides information on a wide range of technical and operational issues.

The guide presents detailed case studies of the original Houston QuickRide HOT lane system prior to the reconstruction of the I-10 Katy Freeway, the SR 91 Express Lanes, and the original San Diego I-15 HOT lane facility, as well as managed lane feasibility studies in Colorado and California. The guide also benefited from a thoughtful peer review by respected industry professionals.

As a 2003 document, the guide is clearly dated and was largely replaced by the *Priced Managed Lane Guide* (*36*). At the time it was prepared, each of the four operating HOT facilities in the United States was fully barrier-separated, and three had single points of access and egress. Today's facilities offer multiple access points, and many have striped separation only. The facilities explored in the guide also predate the widespread use of social media and smartphone applications. While dated, the guide provides an excellent opportunity to assess what issues have evolved in the past 10 years and those that remain essentially unchanged in the design, implementation, and operation of priced managed lanes.

NCHRP Report 414: HOV Systems Manual (1998)

The 1998 *HOV Systems Manual* (*38*) was the first such comprehensive nationally funded guide to reflect extensive HOV lane experiences that at the time included more than 50 projects and over 1000 mi of lane treatments. It addressed general planning, design, and operational experiences with an equal focus on freeway and arterial lanes. The guide reflected the breadth of experiences at the time and was not based on any in-depth research activities that weighed a best or recommended practice where various standards of practice were being applied. Planning provided a solid orientation to the managed lane concept and covered a wide range of topics from the planning process, evaluation criteria, demand estimation methods, and agency roles and policies. Design addressed design vehicles, general design considerations, typical sections, access layouts, termini conditions, enforcement provisions, HOV bypasses at metered ramps and toll plazas, signing and pavement markings, transit support facilities, incident management, and maintenance needs. Operations addressed the basic approaches to operation—exclusive right of way, concurrent flow, reversible flow, and contraflow. Minimum and maximum vehicle operation thresholds are presented for each type of operation. Eligibility and hours of operation are explored based on project experiences at the time. No discussion of ETC is included since this technology did not exist then. Since this guide was published, the cumulative lane mileage of HOV and tolled express lanes has more than tripled, and a number of HOV lanes cited as examples in various inventories have been altered in keeping with the need to maintain high performance standards.

This document lacks the extensive experiences generated from the past two decades of managed lane implementation and operation, notably the widespread use of ETC, improved integration of transit designs and operations into express lanes (particularly related to online stations), expanded experience base of lane and access designs, greater complexity of needs associated with signing and pavement markings, shift in agency sponsorship of projects and operations to more toll and private entities, and greater focus on real-time lane management versus fixed time-of-day eligibility and access rules.

There is particular need for research in addressing the best performing lane configurations and separation designs, access treatments, signing, and pavement markings. This research must place context around the widely diverging operation and policy needs often comprising projects of a regional system in which many variables are different from one corridor to the next.

NCHRP Report 694: Evaluation and Performance Measurement of Congestion Pricing Projects (2011)

Performance monitoring for congestion pricing projects accomplishes three important purposes:

- To ensure that they are functioning as efficiently as possible and make adjustments to operational policies if they are not.
- To quantify and validate the different benefits these facilities deliver.
- To document the successful application of congestion pricing in support of their expanded use.

NCHRP Report 694 (*47*) provides comprehensive guidelines to help agencies identify appropriate performance measures for congestion pricing projects, collect the necessary data, track and evaluate performance, and communicate the results to decision makers, users, and the general public. The research was informed by case studies of 12 pricing projects. They included variably priced managed lanes, toll facilities with variable pricing, and cordon and area pricing.

The guidelines provide tailored recommendations on performance monitoring for each of these pricing forms. They address how and when to put evaluation and performance measurement programs in place, how to identify and develop appropriate performance measures, and how data are collected. The guidelines identify a total of 75 performance measures grouped into eight evaluation areas. While the guidelines attempt to identify as broad a range of goals and performance measures as possible, they also recognize that resources supporting performance evaluation are often constrained. Therefore, the guidelines offer recommendations on which measures are particularly effective in the managing priced facilities and conveying the effects of congestion pricing projects to the public when funds for more extensive monitoring programs are not available.

TCRP Report 95: HOV Facilities, Traveler Response to Transportation System Changes (2006)

TCRP Report 95: Chapter 2, HOV Facilities (*48*) covers the traveler response to high-occupancy-vehicle applications, except for busways primarily on their own alignment, which are addressed in Chapter 4, "Busways, BRT and Express Bus." The overarching objective of the *Traveler Response to Transportation System Changes Handbook* is to equip members of the transportation profession with a comprehensive, readily accessible, interpretive documentation of results and experience obtained across the United States and elsewhere from (a) different types of transportation system changes and policy actions, and (b) alternative land use and site development design approaches. While the focus is on

contemporary observations and assessments of traveler responses as expressed in travel demand changes, the presentation is seasoned with earlier experiences and findings to identify trends or stability, and to fill information gaps that would otherwise exist. Comprehensive referencing of additional reference materials is provided to facilitate and encourage in-depth exploration of topics of interest. Travel demand and related impacts are expressed using such measures as usage of transportation facilities and services, before-and-after market shares and percentage changes, and elasticity.

TCRP Report 95: Chapter 2, HOV Facilities covers the breadth of HOV facilities, inclusive of supportive features, but without examining supportive features in detail. Express bus operations and park-and-ride and park-and-pool facilities are supportive features that enhance the operation of many HOV facilities. These are the subjects of Chapter 4, "Busways, BRT and Express Bus," and Chapter 3, "Park-and-Ride/Pool." The traveler response to and related implications of high-occupancy toll lanes and similar value pricing programs are found in Chapter 14, "Road Value Pricing" (published 2003). Some limited post-2003 HOT lane updates are provided herein.

The findings in the handbook are intended to aid—as a general guide—in preliminary screening activities and quick turnaround assessments. The handbook is not intended for use as a substitute for regional or project-specific travel demand evaluations and model applications, or other independent surveys and analyses.

NCHRP Web-Only Document 191: Analysis of Managed Lanes on Freeway Facilities (2012)

Researchers on NCHRP Project 3-96 (*39*) were tasked with developing guidelines for performance evaluation of managed lane facilities on freeways. They found that there were considerable activities in the development of performance measures for ML facilities, as well as evaluation of ML operational strategies in microscopic simulation. However, there was relatively little research on the development of an analytical framework and methodology for analyzing freeway segments with MLs in the context of the *Highway Capacity Manual*. The research team developed a methodological framework to evaluate performance of freeway facilities based on the concept of parallel lane groups of MLs and GP lanes.

Researchers developed different modules within that framework, including the characterization of ML speed-flow relationships, frictional effects of speed in adjacent lanes, adjustments for cross-weave effects, and development of side-by-side facility-wide ML and GP lane performance measures. Thus, the proposed methodology is sensitive to different GP lane and ML segment types (basic, weaving, etc.) and separation styles (none, buffer, or barrier), and is capable of analyzing extended facilities across multiple time periods. Key findings of the research included:

- Continuous-access MLs were by far the most common type of implementation, consisting of a single ML separated from the neighboring GP lanes by only pavement markings. Their performance degrades significantly due to decreased maneuverability when traffic density on the GP lanes reaches or exceeds a certain level.

- No significant frictional effects were observed for barrier-separated MLs; however, for single-lane barrier-separated MLs, the presence of a barrier was shown to have reduced the speed and the level of maneuverability, even at low volume levels.
- For ML facilities that allow access only at intermittent access segments, cross-weave maneuvers were observed at access segments with close upstream GP lane on-ramps.

Among their recommended topics for future research, the authors of *NCHRP Web-Only Document 191* suggested:

- Beginning and end point designs of ML facilities.
- Special configurations of ML access points, such as grade-separated ramp access.
- A field-data-based approach to estimating capacity-reducing effects of ML cross-weave maneuvers on the GP lanes.

AASHTO Guide for the Design of Park-and-Ride Facilities (1992)

This guide (*43*) addresses both planning and design of park-and-ride facilities serving rail and bus transit, although the majority of information pertains to bus transit operations. Planning topics include selection criteria for sizing and locating facilities and evaluation strategies. Design topics include optional physical layouts for surface and structured parking, traffic circulation within and in the vicinity of the facility, and related topics including kiss-and-ride provisions, bus loading areas, lighting, security, accessibility needs, amenities, joint facilities, maintenance, and environmental considerations. Illustrations and photos of example spatial layouts, guide signing, and pavement markings are included. Linkages to transportation demand management, HOV lanes, and related congestion management actions are presented.

Park-and-ride facilities are perhaps the most commonly supported facility investment associated with managed lanes, and many legacy HOV lane projects include park-and-ride facilities. The majority of these facilities are located adjacent to or near the managed lanes, and are sometimes given direct access to the bus loading area within the park-and-ride lot. The first such park-and-ride facilities located with managed lanes were implemented in the mid-1970s. This reference does not include a discussion of direct-access ramp treatments with managed lanes, which is covered in a companion AASHTO document, *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*).

While the physical design of park-and-ride facilities has not changed markedly over the years, this document lacks an update to reflect some changes in bus loading areas and current adopted technologies to better communicate with users. For example, design for sawtooth bus bays now need to account for National Transportation Safety Board recommendations for passenger protection, and ITS treatments can better direct patrons to available spaces and bus routing status. Bus operators regularly include provisions for bike racks on vehicles, and this added length is not accounted for in bus loading templates. With extensive conversion of HOV lanes, the direct-access features originally serving buses have been opened in some locations to general tolled traffic. The impacts and benefits of express lanes (either converted from HOV or new facilities) need further research with respect to impacts to bus transit and park-and-ride facilities.

FHWA Freeway Geometric Design for Active Traffic Management in Europe (2011)

Continued growth in travel on congested urban freeway corridors exceeds the ability of agencies to provide sufficient solutions and alternatives based on traditional roadway expansion and improvement projects. Several countries are implementing managed motorway concepts to improve motorway capacity without acquiring more land and building large-scale infrastructure projects. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a scanning study of England, Germany, the Netherlands, and Spain to examine the use of innovative geometric design practices and techniques to improve the operational performance of congested freeway facilities without compromising safety (*46*).

Managed motorways are a combination of active or dynamically managed operational regimes, specific designs of infrastructure, and technology solutions. The concept uses a range of traffic management measures to actively monitor the motorway and dynamically control speeds, add capacity, and inform road users of conditions on the network with the objective to optimize traffic and safety performance. Examples include shoulder running, variable mandatory speed limits, lane control signals, and driver information using variable message signs. Managed motorways increase journey reliability and throughput of a motorway by speed management and increase capacity by shoulder running.

Recent Literature

Each of the documents discussed previously, though comprehensive in content, is not sufficient to address all of the current issues or the complexity associated with managed lanes. To further document the profession's existing knowledge on topics related to managed lanes, the team identified additional relevant resources that go beyond standard references. A full-time librarian was utilized to help conduct the literature review using manual queries and online databases. Resources such as the Transportation Research Information Service were found to be helpful during the review. Due to the large number of sources available in the literature databases, the research team confined the search to domestic sources that were published within the last 10 years. The research team attempted to find diversity among various topical areas and geographic region when reviewing and summarizing the literature.

The following sections present key findings from the review of literature, as scoped by the draft outline presented at the beginning of the project. A change made in the outline between the amplified work plan and this chapter is the addition of a section on forecasting due to the number of references identified on that topic.

A list of key references was created for each section that had relevant literature, and in some cases, a short summary of key points that were derived from selected references are included. Those key references are presented in a table similar to Table 42. Expanded summaries for a limited selection of references are provided below their respective tables.

Some topics did not have any published literature within the last 10 years, or the topic was addressed in a source on a related topic. The outline of this chapter is consistent with the expected outline of the Guidebook that will be developed at the conclusion of the project.

PLANNING CONSIDERATIONS

Planning and Programming

Needs, Goals, and Objectives Identification

Table 43 lists the key references for this subtopic.

Table 43. Key references for needs, goals, and objectives.

Reference	Num
Evaluating Criteria for Adapting HOV Lanes to HOT Lanes: Development and Application of HOT START Software Tool	*54*
Advancing Congestion Pricing in the Metropolitan Transportation Planning Process: Four Case Studies	*55*

Intended Customers/Markets

Table 44 lists the key references for this subtopic.

Table 44. Key references for intended customers/markets.

Reference	Num
Examining the Differences Between Travelers' Revealed Versus Actual Travel Time Savings	*56*
Empirical Evidence from the Greater Toronto Area on the Acceptability and Impacts of HOT Lanes	*57*
Can Psychological Traits Help Predict the Use of Priced Managed Lanes?	*58*
Explaining Willingness-to-Pay for Tolls: The Role of Individual Self-Interest, Concern for the Greater Good, and Socio-Political Factors	*59*
Analysis of Fleet Composition and Vehicle Value for the Atlanta I-85 HOT Lane	*60*
Investigating Changes in Willingness-to-Pay for Managed Lane Systems: A Quasi-Panel Approach	*61*

Strategy Selection and Operational Approach

Table 45 lists the key references for this subtopic.

Table 45. Key references for strategy selection and operational approach.

Reference	Num
A Feasibility Study for Converting HOV Lanes to Managed Lanes in Dallas, Texas	*62*
HOT Lane Policies and Their Implications	*63*
Operational Performance Management of Priced Facilities	*64*
Effective Approaches for Advancing Congestion Pricing in a Metropolitan Region	*65*
Policy Options Evaluation Tool for Managed Lanes (POET-ML) Users Guide and Methodology Description	*66*
Assessing Highway Tolling and Pricing Options and Impacts, Volume 1: Decision-Making Framework	*67*

Partnerships/Agreements

Table 46 lists the key references for this topic.

Table 46. Key references for partnerships and agreements.

Reference	Num
Minnesota's Proposal for Urban Partnership Agreement: Case Study of Political and Institutional Issues in Congestion Pricing	*68*
Georgia's Approach to Congestion with Four T's: Tolling, Transit, Telework, and Technology	*69*

Funding and Finance

Table 47 lists the key references for this subtopic.

Table 47. Key references for funding and finance.

Reference	Num
Benefit-Cost Analysis of Variable Pricing Projects: QuickRide HOT Lanes	*70*
Simulation-Based Investigation on High-occupancy Toll Lane Operations for Washington State Route 167	*71*
Benefit and Cost Analysis of the I-394 MnPASS Program	*72*
Benefit-Cost Analysis of Variable Pricing Projects: SR-91 Express Lanes	*73*
Trade-Off for Road Pricing Between Transportation Performance and Financial Feasibility	*74*
Economic and Financial Feasibility of Truck Toll Lanes	*75*
State Route 91 Value-Priced Express Lanes: Updated Observations	*76*
Robust Pricing of Transportation Networks Under Uncertain Demand	*77*
Paying for Predictability: US Managed Lanes Projects Special Report	*78*
Managed Lanes are HOT! Unique Risks and Benefits Versus Traditional Tolling	*79*
US Managed Lanes: Empirical Data Steers Credit Analysis Special Report	*80*

Concept of Operations

No information on this topic was found in the literature.

Policy and Legislative Considerations

Table 48 lists the key references for this topic.

Table 48. Key references for policy and legislative considerations.

Reference	Num
Integrating Transit with Road Pricing Projects	*81*
Minnesota's Proposal for Urban Partnership Agreement: Case Study of Political and Institutional Issues in Congestion Pricing	*68*
Analysis of Regulation and Policy of Private Toll Roads in a Build-Operate-Transfer Scheme Under Demand Uncertainty	*82*
Regulating Concessions of Toll Motorways: An Empirical Study on Fixed vs. Variable Term Contracts	*83*
State and Federal Legislative Issues for Managed Lanes	*84*
Cost/Benefit Analysis of Converting a Lane for Bus Rapid Transit Phase II Evaluation and Methodology	*85*
Dual Influences on Vehicle Speed in Special-Use Lanes and Critique of US Regulation	*86*
Performance Evaluation of I-394 MnPASS Express Lanes in Minnesota	*87*

A review for the Florida Department of Transportation (FDOT) (*81*) on the consideration of transit service in the design and operation of managed lane facilities resulted in a series of recommendations for optimal statewide policy. These considerations were:

- The projected market for public transportation in the corridor or on the network.
- The financial commitments and project components to enhance transit service, which are commensurate with the market potential in a particular corridor or region.
- The accommodation of the various financial constraints and requirements of FDOT, its districts, and Florida's Turnpike Enterprise, local expressway authorities, regional transportation authorities, and transit agencies.
- Recognition of public transportation's contribution to choice and congestion reduction in the corridor (*81*).

For the I-394 MnPass Lanes in Minnesota, the Minnesota State Legislature authorized the HOV-to-HOT lane conversion in 2003 (*87*). Project goals were explicitly defined in the legislation and helped to guide overall project planning and development. The legislature primarily wanted the I-394 MnPass Lanes to improve the overall operation of the corridor by making better use of existing capacity. The goals included maintaining or enhancing the existing level of service for both non-toll-paying and toll-paying customers, developing reasonable revenue expectations, and keeping customers satisfied with the experience of travel on the I-394 MnPass Lanes. Specifically, Minnesota DOT (MnDOT) staff interpreted that the MnPass Lanes had to operate at an LOS C or better. Any excess revenue from the project had to be split evenly to cover transit service and to provide for other physical improvements. At the time of the authorizing legislation, there was uncertainty about the revenue-generating potential of the project.

Pricing

Table 49 lists the key references for this subtopic.

The I-394 MnPass Lanes had a dynamic pricing algorithm that ensured free-flow conditions even as traffic increased (*88*). A minimum toll for using the MnPass Lanes was set at $0.25, and the maximum toll was set at $8.00. The algorithm automatically adjusts the price up or

down in relationship to the density of vehicles detected in the lanes. When a change in the density is detected by the roadway sensors, the toll is adjusted per a look-up table.

Table 49. Key references for pricing.

Reference	Num
Fine-Tuning Pricing Algorithms for High-Occupancy/Toll (HOT) Lanes	*88*
Managed Lane Operations—Adjusted Time of Day Pricing vs. Near-Real Time Dynamic Pricing, Volume 1: Dynamic Pricing and Operations of Managed Lanes	*89*
Differentiated Road Pricing, Express Lanes, and Carpools: Exploiting Heterogeneous Preferences in Policy Design [with Comments]	*90*
Federal Highway Administration (2013, publication pending) Variable Pricing Synthesis: A Review of Dynamic and Fixed Variable Pricing Systems	

Enforcement Approach

Literature on enforcement can be found later in this appendix in the Operations and Maintenance section.

Operational Changes

Table 50 lists the key references for this subtopic.

Table 50. Key references for operational changes.

Reference	Num
Operational Performance Management of Priced Facilities	*64*
I-394 MnPASS High-Occupancy Toll Lanes: Planning and Operational Issues and Outcomes (Lessons Learned in Year 1)	*91*
Life-Cycle Graphical Representation of Managed High-Occupancy Vehicle Lane Evolution	*92*
Dual Influences on Vehicle Speeds in Special-Use Lanes and Policy Implications	*93*

A study conducted by the University of California at Berkeley assessed the impact of regulation that restricts, or bans, specific classes of low-emitting vehicles from slow-moving carpool lanes (*93*). The study used data that were collected from freeway carpool facilities in the San Francisco Bay Area in a model that used kinematic wave analysis to produce different outcomes. A conclusion from the study was that limiting access to low-emission vehicles and pushing them to the adjacent general-purpose lanes would cause more overall congestion in the corridor.

Public Involvement and Outreach

Table 51 lists the key references for this topic.

Common Messages and Public Education

Specific literature on this subtopic can be found in Table 51.

Project Champion

Specific literature on this subtopic can be found in Table 51.

Engaging Policy Makers

Specific literature on this subtopic can be found in Table 51.

Engaging the Media and General Public

Specific literature on this subtopic can be found in Table 51.

Table 51. Key references for public engagement and outreach.

Reference	Num
Value Pricing Outreach and Education: Key Steps in Reaching High-Occupancy Toll Lane Consensus in Minnesota	*94*
Compilation of Public Opinion Data on Tolls and Road Pricing	*95*
Achieving Majority Public Support for Urban Road Pricing: Preserving the Driver's Right to Choose	*96*
Value Pricing Education and Outreach Model: 1-394 MnPASS Community Task Force	*97*
Addressing Equity in Political Debates over Road Pricing	*98*
Equity, Pricing, and Surface Transportation Politics	*99*
I'll Tell You What I Think! A National Review of How the Public Perceives Pricing	*100*
Marketing the Managed Lanes Concept	*101*
Road Pricing: Public Perceptions and Program Development	*102*
Road Pricing Communication Practices	*103*
High-Occupancy Toll (HOT) Lanes Marketing Toolkit	*104*

Project Delivery and System Integration

Literature on this topic can be found in the project deployment section of this appendix, as it pertains to the policy and planning implications for implementing managed lanes.

Interoperability/Regional Consistency

Table 52 lists the key reference for this subtopic.

Table 52. Key reference for interoperability/regional consistency.

Reference	Num
Migrating to US Nationwide Electronic Tolling Interoperability	*105*

Federal and State Environmental Requirements and Permitting

No information on this topic was found in the literature.

Decision-Making Process on Management Strategy and Managed Lane Facility Type

Table 53 lists the key references for this subtopic.

Table 53. Key references for decision-making process on management strategy and managed lane facility type.

Reference	Num
Evaluating Criteria for Adapting HOV Lanes to HOT Lanes: Development and Application of HOT START Software Tool	*54*
Operational Performance Management of Priced Facilities	*64*
Life-Cycle Graphical Representation of Managed High-Occupancy Vehicle Lane Evolution	*92*

Forecasting

Table 54 lists the key references for this subtopic.

Table 54. Key references for forecasting considerations.

Reference	Num
Congestion Pricing on a Road Network: A Study Using the Dynamic Equilibrium Simulator METROPOLIS	*106*
Choice Models of Route, Occupancy, and Time of Day with Value-Priced Tolls	*107*
Explaining High-Occupancy-Toll Lane Use	*108*
Managed Lanes—Traffic Modeling	*109*
Simulation Analysis of Truck-Restricted and High-Occupancy Vehicle Lanes	*110*
Development and Comparison of Choice Models and Tolling Schemes for High-Occupancy/Toll (HOT) Facilities	*111*
Simulating High-Occupancy-Toll Lane Operations	*112*
Simulating Realistic Shockwave Propagation on HOT Lanes	*113*

DESIGN ELEMENTS

Safety Performance

Table 55 lists the key references for this topic.

Table 55. Key references for safety performance.

Reference	Num
Safety Benefits of Converting HOV Lanes to HOT Lanes: Case Study of the I-394 HOT Lanes	*114*
Comparison of Collisions on HOV Facilities with Limited and Continuous Access	*115*
Safety Impacts of Freeway Managed Lane Strategy: Inside Lane for High-Occupancy Vehicle Use and Right Shoulder Lane as Travel Lane During Peak Periods	*116*

An Empirical-Bayes statistical estimation procedure was conducted on the I-394 MnPass Lanes in Minnesota (*114*) and found the overall number of crashes to be reduced by 5.3 percent. The economic benefit was found to be $5 million during the period of 2006 to 2008. AADT data were used from 1998 to 2008. A four-year observation period was used before the start of tolling as well as a two-year post deployment observation period. Crash

data of interstate highways in the Minneapolis–St. Paul (Twin Cities) seven-county metropolitan area from MnDOT were used. The I-394 MnPass Lanes opened for operation in 2005. The authors of the paper are not confidant their results can be attributed to other HOT lane projects because of the limited research on this issue, and because many HOT lanes have opened just recently.

A study was conducted by the University of California, Institute of Transportation Studies (*115*) to examine the safety impacts of continuous-access versus limited-access managed lanes. Eight different corridors were evaluated by looking at the traffic collision patterns based on the (a) differences in collision distribution, severity, types of collisions, and per-lane traffic utilization; (b) spatial distribution of collision concentrations by using a continuous risk profile (CRP) approach; and (c) collision rates in the vicinity of access points in HOV lanes with limited access. The corridors that were defined for analysis were selected by regional traffic engineers on the basis of local knowledge and perspective. A major caveat from the study was that HOV facilities with continuous access are in operation only during the morning and afternoon peak hours—generally 5 to 9 a.m. and 3 to 7 p.m. Alternatively, the HOV facilities with limited ingress and egress access are in operation 24 hours a day. The study showed that limited-access HOV facilities appear to offer no safety advantages. In fact, at least in the corridors examined, compared to continuous-access HOV lanes, limited-access HOV lanes have a higher proportion of collisions across lanes of the freeway, a higher number of collisions per mile, and a higher ratio of collision distribution to traffic volume distribution, and collisions are of greater severity. These differences are not induced by the weaving traffic movements in the vicinity of ingress/egress areas in limited-access HOV lanes.

General Geometric Design Considerations

Design and Operational Consistency across Local, Regional, and National Systems

Table 56 lists the key reference for this topic.

Table 56. Key reference for design and operational consistency.

Reference	Num
Interoperability Issues on Managed Lane Facilities	*117*

Design Vehicle/Eligibility

No information on this subtopic was found in the literature.

Managed Lane Facility

Table 57 lists the key reference for this topic.

Table 57. Key reference for managed lane facility.

Reference	Num
Single-Lane Issues on Managed Lane Facilities	*118*

Managed Lane Placement with Respect to Mainlanes

No information on this subtopic was found in the literature.

Separation between Managed Lane and Mainlanes

Table 58 lists the key references for this subtopic.

Table 58. Key references for managed lane and mainlane separation.

Reference	Num
Dual Influences on Vehicle Speed in Special-Use Lanes and Critique of US Regulation	*86*
I-394 MnPASS High-Occupancy Toll Lanes: Planning and Operational Issues and Outcomes (Lessons Learned in Year 1)	*91*
Changes in Legal and Illegal Weaving Activity After Restriping of I-85 High-Occupancy-Vehicle Lanes in Atlanta, Georgia	*119*
Analysis of Operational Interactions Between Freeway Managed Lanes and Parallel, General-Purpose Lanes	*120*
Examination of SR 167 HOT Lane Violation Patterns	*121*
Best Practices: Separation Devices Between Toll Lanes and Free Lanes	*122*
HOT Lane Buffer and Mid-Point Access Design Review Report	*123*
Cross-Section Designs for the Safety Performance of Buffer-Separated High-Occupancy Vehicle Lanes	*13*
Analysis of Reduction in Effective Capacities of High-Occupancy Vehicle Lanes Related to Traffic Behavior	*124*

The Georgia Institute of Technology conducted an evaluation (*119*) of legal and illegal weaving during the conversion of the I-85 HOT Lanes in Atlanta, Georgia. At the time of the report, the I-85 Express Lanes were not officially opened yet. However, a final report is expected to be issued by the Georgia Department of Transportation soon. The research team collected video data between I-285 and GA 316 and quantified movements for an entire year before the start of tolling.

Access to Managed Lane

Table 59 lists the key references for this subtopic.

Table 59. Key references for access to managed lane.

Reference	Num
Analysis of Reduction in Effective Capacities of High-Occupancy Vehicle Lanes Related to Traffic Behavior	*124*
Quantifying Cross-Weave Impact on Capacity Reduction for Freeway Facilities with Managed Lanes	*125*
Intermediate Access to Buffer-Separated Managed Lanes	*32*
Assessment and Validation of Managed Lanes Weaving and Access Guidelines	*126*
Katy Freeway: An Evaluation of a Second-Generation Managed Lanes Project	*127*

A study was done to investigate the cross-weaving on managed lanes as a function of different roadway geometric configurations as well as traffic conditions. A microscopic simulation

model was built and calibrated on the basis of video data collected along I-635 in Dallas, Texas. Multiple scenarios were tested to explore the effect of the following parameters: number of GP lanes, cross-weave demand, and cross-weaving length. A set of capacity adjustment factors was determined to account for this effect as a function of those parameters. Results showed that the capacity-reducing effect was higher with a reduction in cross-weaving length, an increase in the number of GP lanes, or a rise in cross-weave demand volumes. The results are important in evaluating the operational performance of freeway segments in the presence of concurrent GP lanes and MLs in a *Highway Capacity Manual* context. The study also produced a number of different cross-weaving reduction factors, as seen in Table 60 (*125*).

Table 60. Cross-weaving reduction factors (*125*).

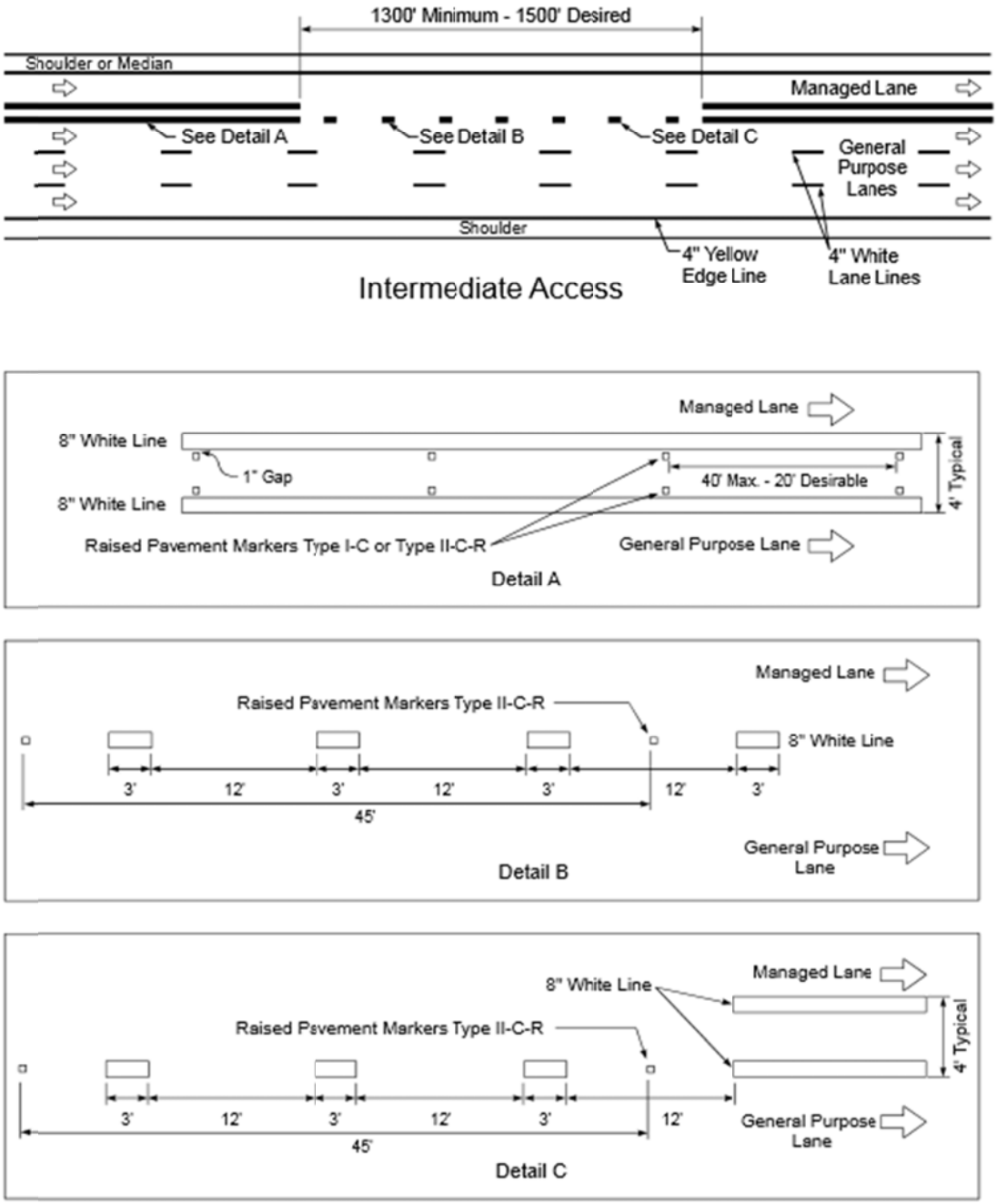
CRF (%) by Cross-Weave Flow (vph)					
Low-min (ft)	**100**	**200**	**300**	**450**	**600**
4 GP Lanes					
1,500	1.63	3.27	4.49	5,71	6.53
2,000	1.02	2.24	3.67	4.69	5.31
2,500	0.20	1.63	3.27	4.08	4.69
3 GP Lanes					
1,500	1.22	3.06	3.88	5.51	6.12
2,000	0.82	2.04	3.47	4.29	4.69
2,500	0.20	1.43	2.65	4.08	4.29
2 GP Lanes					
1,500	1.02	2.54	3.67	5.10	5.31
2,000	0.61	2.04	3.06	4.29	4.90
2,500	0.00	1.22	2.24	3.27	4.08

Source: Liu, X., Y. Wang, B. Schroeder, and N. Rouphail. Quantifying Cross-Weave Impact on Capacity Reduction for Freeway Facilities with Managed Lanes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2278*, Table 2, p. 177. Copyright, National Academy of Sciences, Washington, D.C., 2012. Reproduced with permission of the Transportation Research Board.

A TxDOT-sponsored study by the Texas Transportation Institute (*32*) developed recommended guidelines for the design of access points on buffer-separated managed lane facilities. One recommendation is shown in Figure 44.

Researchers (*126*) used the findings from a previous study as a basis for a study to recommend spacing requirements for access points to managed lanes with respect to the location of entrance and exit ramps on the general-purpose lanes of the freeway. The results were based on microscopic simulation using VISSIM. The simulation model was calibrated using data collected on I-635 (LBJ Freeway) in Dallas, Texas. A genetic algorithm was used in the calibration. The model was subsequently validated using data collected at a nearby site along I-635. The weaving was analyzed as a Type C two-sided weave. Capacity was estimated by gradually increasing flow in the general-purpose lanes for each set of conditions until the simulation model throughput was less than the input flows, indicating the formation of queues. The specific conditions included ramp flows (500 to 1250 veh/hour), ramp to

managed lane flows (100 to 400 veh/hour), general-purpose lanes to managed lane flows (200 to 800 veh/hour), and length of weave (1000 to 4000 ft).



Notes:

All pavement marking materials shall meet the required Departmental Material Specifications as specified in plans.

⇨ = Direction of travel.

Source: (*126*)

Figure 44. Recommended design of intermediate access opening.

The principal determinant for spacing was the weaving flow (ramp to managed lane flow), with a minimum weaving distance of 2000 to 3500 ft for flows from 200 to 400 veh/hour. Researchers concluded that a desirable weaving distance was 4000 ft for this freeway section with four general-purpose lanes. The guidelines that were recommended from the report can be found in Table 61.

Table 61. Guidelines for weaving distances on managed lanes.

v_{rm} or v_{mr}, veh/hour	Weaving Distance			
	Minimum		Desirable	
	Four general-purpose lanes, ft	Per general-purpose lane, ft/lane	Four general-purpose lanes, ft	Per general-purpose lane, ft/lane
up to 200	2000	500	4000	1000
200 to 300	2500	625	4000	1000
300 to 400	3000	750	4000	1000
over 400	3500	875	4000*	1000*

Note: Recommendations for minimum weaving distance between a right-side entrance ramp and the left-side access to a managed lane (v_{rm}) or between the left-side access to a managed lane and a right-side exit ramp (v_{mr}).
Source: (*127*).
*A direct connection to the managed lane should be considered.

Transit Considerations

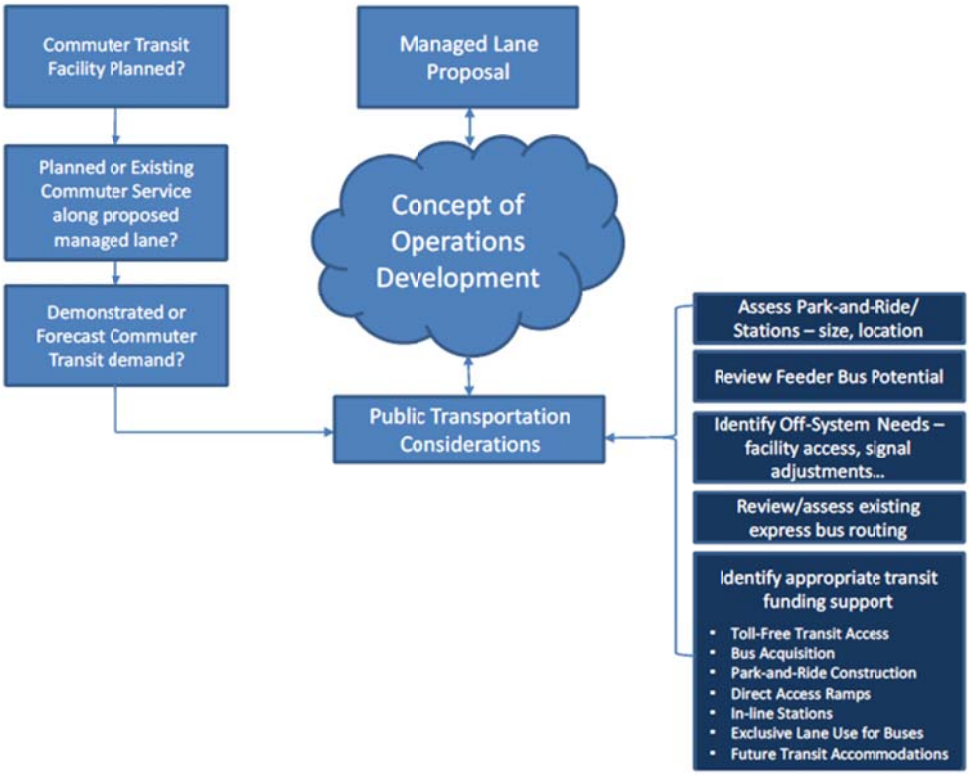
Table 62 lists the key references for this subtopic.

Table 62. Key references for transit considerations.

Reference	Num
Integrating Transit with Road Pricing Projects	*81*
Impacts to Transit from Variably Priced Toll Lanes: Results from U.S. Department of Transportation Urban Partnership Agreements	*128*
Geometric Design Guide for Transit Facilities on Highways and Streets—Phase I Interim Guide	*129*
NCHRP Report 143: Bus Use of Highways, State of the Art	*130*
NCHRP Report 155: Bus Use of Highways Planning and Design Guidelines	*131*
TCRP Report 90: Bus Rapid Transit, Volume 1: Case Studies in Bus Rapid Transit	*132*
TCRP Report 90: Bus Rapid Transit, Volume 2: Implementation Guidelines	*133*
TCRP Report 95: Traveler Response to Transportation System Changes Handbook, Third Edition: Chapter 2, HOV Facilities	*48*

A review of road pricing projects (*81*) conducted for the Florida Department of Transportation found that public transportation was given consideration in the planning, design, and operation of various managed lane projects. The five projects assessed included the I-15 and I-805 Managed Lanes in San Diego, the SR 520 Bridge and SR 167 HOT Lanes in Seattle, and the I-85 Express Lanes in Atlanta. Topics addressed included the consideration of statewide policy, financial commitments of various partners, role of tolling agencies, demand forecasting, public outreach and marketing, and impacts of federal legislation (e.g., MAP-21). A belief conveyed in the report was the concept that transit improvement can be had with very little transit investment. An appendix of congestion pricing projects appears in the report, with

information dated from 2011. The Texas A&M Transportation Institute and Government Accountability Office reports are cited as sources for the appendix. The FDOT report also provided a conceptual framework (shown in Figure 45)for considering public transit in the design and operation of a managed lane or other priced facility.



Source: (*81*)

Figure 45. Conceptual framework from the FDOT review of transit.

Truck Considerations (Including Freight/Truck-Only Facilities)

Table 63 lists the key references for this subtopic.

Table 63. Key references for truck considerations.

Reference	Num
Guide for Geometric Design and Operational Factors That Impact Truck Use of Toll Roads	*134*
Operational Aspects of Exclusive Truck Roadways	*135*
Planning Truck-Only Lanes: Emerging Lessons from the Southern California Experience	*136*
Safety Evaluation of Truck Lane Restriction Strategies Using Micro Simulation Modeling	*137*
Simulation of Exclusive Truck Facilities on Urban Freeways	*138*
Separation of Vehicles—CMV-Only Lanes	*139*

Issues Unique to HOV Lane Conversion

Table 64 lists the key references for this subtopic.

Table 64. Key references for HOV lane conversion.

Reference	Num
ATDM Analysis Brief #3: Example Application (HOV to HOT) of ATDM Capacity and Operations Analysis	*140*
Consideration for High-Occupancy-Vehicle to High-Occupancy Toll (HOT) Lanes Study	*141*
Guidebook for HOV-to-HOT Lane Adaptation: HOT START Software User's Guide	*142*
So You Want to Make a High-Occupancy Toll Lane? Project Manager's Guide for Conversion from High-Occupancy Vehicle Lane to High-Occupancy Toll Lane	*143*
A Case Study of the Design Issues Associated with HOV-to-HOT Conversion	*144*
HOV-to-HOT Screening Checklist	*145*

Design Variances

No information on this subtopic was found in the literature.

Flexible Design Philosophies

No information on this subtopic was found in the literature.

System Integration Considerations

No information on this subtopic was found in the literature.

Operational Impacts on Design

Operational Strategy's Impact on Design

No information on this subtopic was found in the literature.

Tolling Systems

No information on this subtopic was found in the literature.

Enforcement Systems

Literature on eligibility validation and enforcement can be found later in this appendix in the Operations and Maintenance section.

Capacity

Table 65 lists the key references for this topic.

Table 65. Key references for capacity.

Reference	Num
Dual Influences on Vehicle Speed in Special-Use Lanes and Critique of US Regulation	*86*
Analysis of Reduction in Effective Capacities of High-Occupancy Vehicle Lanes Related to Traffic Behavior	*124*
Comparison of Capacities of High-Occupancy-Vehicle and General-Purpose Lanes	*146*

Traffic Control Devices

Table 66 lists the key references for this topic.

Table 66. Key references for traffic control devices.

Reference	Num
Traffic Control Devices for Managed Lanes	*147*
Managed Lane Operations—Adjusted Time of Day Pricing vs. Near-Real Time Dynamic Pricing	*148*

Traffic Control Device Requirements for Specific Operations

No information on this subtopic was found in the literature.

Static Signs

Table 67 lists the key references for this subtopic.

Table 67. Key references for static signs.

Reference	Num
Driver Comprehension of Signing and Marking for Toll Facilities	*41*
Driver Comprehension of Managed Lane Signing	*149*

Dynamic Message Signs

No information on this subtopic was found in the literature.

Lane Control Signals (including Variable Speed Limits)

Table 68 lists the key reference for this subtopic.

Table 68. Key reference for lane control signals.

Reference	Num
Managed Lane Operations—Adjusted Time of Day Pricing vs. Near-Real Time Dynamic Pricing	*148*

A report (*148*) from the University of Florida for FDOT assessed the potential impacts that a variable speed limit (VSL) has on the operation of the I-95 HOT Lanes. Researchers used CORSIM to simulate a number of different VSL scenarios. A significant finding from the report was that throughput was found to increase for most of the VSL scenarios tested by a

maximum of 30 to 90 vehicles over a given 15-minute time period. The concept of VSL was found to improve the operation of the lane. The study did not attempt to assess optimum threshold, sign locations, or detector locations.

Pavement Markings

No information on this subtopic was found in the literature.

Other Methods of Disseminating Information

No information on this subtopic was found in the literature.

IMPLEMENTATION AND DEPLOYMENT

Project Implementation

Design Review

Table 69 lists the key references for this subtopic.

Table 69. Key references for design review.

Reference	Num
A Guide to Configuration Management for Intelligent Transportation Systems	*150*
Developing Functional Requirements for ITS Projects	*151*

Schedule/Installation

No information on this subtopic was found in the literature.

Testing and System Acceptance

Table 70 lists the key reference for this subtopic.

Table 70. Key reference for testing and system acceptance.

Reference	Num
Testing Programs for Transportation Management Systems: A Technical Handbook	*152*

Project Deployment

Project Delivery

Table 71 lists the key references for this subtopic.

Table 71. Key references for project delivery.

Reference	Num
Katy Freeway: An Evaluation of a Second-Generation Managed Lanes Project	*127*
Delivering Transportation Infrastructure Through Public-Private Partnerships: Planning Concerns	*153*
Assessing the Effectiveness of Infrastructure Public-Private Partnership Programs and Projects	*154*
Flexible Build-Operate-Transfer Contracts for Road Franchising Under Demand Uncertainty	*155*
Research Needs for Virginia Transportation Public-Private Partnership Policy	*156*
Rebuilding Interstates: A Basic To-Do List for Project Delivery	*157*

The project delivery of the Katy Freeway (I-10) Managed Lanes in Houston, Texas, took place within a complex environment of multiple public agencies, stakeholders pressing for influence, and a public dissatisfied with a congested freeway (*127*). The Harris County Toll Road Authority (HCTRA), the Metropolitan Transit Authority of Harris County (METRO), TxDOT, and FHWA were all different government agencies that were involved. The agencies created several agreements that forged the formal relationship that enabled them to successfully navigate the development, construction, and operations of the Katy Freeway and managed lanes. A tri-party agreement was formed between HCTRA, TxDOT, and METRO to implement the Katy Freeway MLs. HCTRA was responsible for maintaining the tollway, TxDOT was responsible for maintaining the general-purpose lanes, and METRO operates the transit service on the managed lanes. Overall, it was found that the series of agreements provided the focus necessary to forge ground-breaking agreements and implement innovative strategies to bring the project to fruition (*127*).

Outreach and Marketing

Literature on this topic can be found in the previous public involvement and outreach sections (seen in Table 51) of this appendix, as it pertains to the implementation and deployment of managed lanes.

Tolling Deployment

Table 72 lists the key references for this subtopic.

Table 72. Key references for tolling deployment.

Reference	Num
Clearinghouse Development and Operations: Comparison of Various ETC Projects	*158*
Exploring Alternative Models for Procuring Back-Office Software and Services	*159*
Technologies that Enable Congestion Pricing: A Primer	*160*

System Phasing and Development Considerations

Table 73 lists the key references for this subtopic.

Table 73. Key references for system phasing and development considerations.

Reference	Num
I-394 MnPASS High-Occupancy Toll Lanes: Planning and Operational Issues and Outcomes (Lessons Learned in Year 1)	*91*
High-Occupancy/Toll Lanes: Phasing in Congestion Pricing a Lane at a Time	*161*

Coordination

Utilities/Cities

No information on this subtopic was found in the literature.

Construction Coordination/Phasing

Table 74 lists the key reference for this subtopic.

Table 74. Key reference for construction coordination/phasing.

Reference	Num
The Implementation of Open Road Tolling on the Illinois Tollway	*162*

Upgrades and Expansions

Table 75 lists the key reference for this subtopic.

Table 75. Key reference for upgrades and expansions.

Reference	Num
Katy Freeway: An Evaluation of a Second-Generation Managed Lanes Project	*127*

OPERATIONS AND MAINTENANCE

General Operations Issues

Pricing

Table 76 lists the key references for this subtopic.

Chan and Wang (*173*) compiled pricing information for a variety of facilities; that information is summarized below.

- For the I-10 and I-110 ExpressLanes in Los Angeles, California: If traffic conditions in the HOT lanes change, tolls will be adjusted to maintain a minimum speed of 45 mph (LOS C). If speeds fall below 45 mph for more than 10 minutes, single-occupant vehicles (SOVs) will be informed by dynamic message signs that entry is restricted only to HOVs. Tolls will range from $0.25 per mile to $1.40 per mile.
- For the METRO HOT Lanes in Houston, Texas: The pricing mechanism of the lanes is intended to maintain a level of service of 1500 vph, or approximately 50 mph (*173*).

Table 76. Key references for pricing.

Reference	Num
High-Occupancy Toll Lane Innovations: I-394 MnPASS	*163*
Dynamic Tolling Strategies for Managed Lanes	*164*
A Feedback-Based Dynamic Tolling Algorithm for High-Occupancy Toll Lane Operations	*165*
A Dynamic Congestion Pricing Strategy for High-Occupancy Toll Lanes	*166*
Dynamic Value Pricing as Instrument for Better Utilization of High-Occupancy Toll Lanes: San Diego I-15 Case	*167*
Optimizing HOT Lane Performance Using Congestion Pricing Algorithms	*168*
Optimal Dynamic Pricing Strategies for High-Occupancy/Toll Lanes	*169*
State-Dependent Pricing for Real-Time Freeway Management: Anticipatory Versus Reactive Strategies	*170*
Model-Based Dynamic Pricing Algorithm for Managed Lanes	*171*
A Unified Framework of Proactive Self-Learning Dynamic Pricing for High-Occupancy/Toll Lanes	*172*
Implementation and Evaluation of Automated Vehicle Occupancy Verification: California PATH	*173*

- For the I-495 HOT Lanes in Virginia: The system will manage traffic in the HOT lanes to maintain speeds of 55 mph by dynamically varying the toll between $0.10 per mile and $1.00 per mile. HOVs with two or more occupants are exempted from the toll. All users of the HOT lanes facility will be required to obtain a switchable transponder to declare their status.
- For the I-25 HOV Express Lanes in Denver: The toll varies between $0.50 and $3.50 according to the time of the day, not traffic conditions. There are two tolling periods: the morning peak period from 5:00 a.m. to 10:00 a.m. and the afternoon period from noon to 3:00 a.m.
- For the MnPass Lanes in Minnesota: The system uses dynamic pricing to set the tolling rate according to traffic conditions with the objective of maintaining speeds around 50 mph. The tolls usually range from $0.50 to $8.00 and are applied in the peak direction and hours: from 6:00 a.m. to 10:00 a.m. in the eastbound direction and from 2:00 p.m. to 7:00 p.m. in the westbound direction. HOVs with two or more passengers and vanpools are not required to have a transponder to use the express lanes. Additionally, pricing varies according to the segment of the facility.
- For the 95 Express in Miami: Dynamic pricing varies the toll from $0.25 to $7.50, although the maximum toll is typically $3.50. The goal is to maintain speeds of 55 mph in the express lanes.

Operation Management

Related literature on this topic can be found under the pricing section (seen in Table 76).

Startup/Opening Guidelines

No information on this subtopic was found in the literature.

Eligibility Validation (Manual and Automated)

Table 77 lists the key references for this subtopic.

Table 77. Key references for eligibility validation.

Reference	Num
Implementation and Evaluation of Automated Vehicle Occupancy Verification: California PATH	*173*
Automated Vehicle Occupancy Verification Systems: Policy and Legal Implications	*174*
Monitoring the Use of HOV and HOT Lanes	*175*
Sensing System Development for HOV/HOT (High-Occupancy-Vehicle) Lane Monitoring	*176*
Automating HOT Lanes Enforcement	*177*

A study conducted by the University of Minnesota evaluated the effectiveness of using infrared cameras to validate vehicle occupancy (*175*). Two different camera setups were assessed during the study: near-wave infrared spectrum and optical video. A pair of Alpha NIR cameras was used in the experiment, and each camera was fitted with an identical fixed-focus lens. Dual-band near-wave infrared images (based on a long- and short-pass filter) proved to be useful for differentiating human skin from other infrared reflective materials. High-resolution color video images were useful for segmenting human-like objects based on skin color. The research team was able to detect vehicle occupants by comparing two images of individuals at wavelengths above and below 1400 nm separately. An accuracy rate of 82 percent was obtained. With a color HD camcorder, the team was able to reach a higher performance rate of 88 percent.

The California Partners for Advanced Transportation Technology (PATH) of the University of California, Berkeley conducted an evaluation of an automated vehicle occupancy verification system for SANDAG and Caltrans as part of the Value Pricing Program Pilot (VPPP) (*173*). The research team tested a number of different scenarios under controlled and uncontrolled situations. Controlled tests were done under the premise that the occupancy of each vehicle was known before each test was conducted (for a total of 546 evaluated cases), and uncontrolled tests were conducted on vehicles in actual traffic for two weeks during all 24 hours of each day. The overall test showed very low accuracy or pass rates. However, none of the technical issues raised as a result were defined to completely stop future development. It was also found that it was technically feasible to achieve a better quality image and better processing output, based on the experience with other comparable studies and advances in state-of-the-art technology (*173*).

A study conducted by the Georgia Tech Research Institute (GTRI) for the Georgia Department of Transportation assessed the feasibility of monitoring HOV/HOT facilities with an imaging system (*176*). The system was proposed to be installed on the median barrier of the managed lanes to acquire data on passing vehicles and determine the occupancy within those vehicles. A lab prototype consisting of an infrared illuminator, a camera, a vehicle trigger, a computer, and software to control the system was integrated and evaluated. Data were recorded at GTRI facilities, sites on the Georgia Tech campus, and also on I-85. The results indicated the practical feasibility of building a system that would be able to provide the data needed to support the operation of HOV/HOT lanes.

Traffic Monitor and Control

No information on this subtopic was found in the literature.

Access Control and Safety

Table 78 lists the key references for this subtopic.

Table 78. Key references for access control and safety.

Reference	Num
Intermediate Access to Buffer-Separated Managed Lanes	*32*
Assessment and Validation of Managed Lanes Weaving and Access Guidelines	*126*
Katy Freeway: An Evaluation of a Second-Generation Managed Lanes	*127*

Enforcement

Table 79 lists the key references for this topic. Summaries for some of the literature appear under specific subtopic headings.

Table 79. Key references for enforcement.

Reference	Num
Implementation and Evaluation of Automated Vehicle Occupancy Verification: California PATH	*173*
Automating HOT Lanes Enforcement	*177*
Enforcement Strategies for High-Occupancy Toll Lanes (08-3025)	*178*
U.S. Patent No. 8,044,824	*179*
Enforcement Issues on Managed Lanes	*180*
Background Paper #8: Toll Technology Considerations, Opportunities, and Risks	*181*
HOV Lane Enforcement Considerations Handbook	*182*

Approaches

A 2011 report from California PATH (*173*) did a review of enforcement approaches across various HOT lanes. These included facilities that at the time of the report were operational or were starting to open. Some of the characteristics may be currently out of date because of operational changes made over time.

Techniques, Tactics, and Technology

Table 80 lists the key reference for this subtopic.

Table 80. Key reference for techniques, tactics, and technology.

Reference	Num
Implementation and Evaluation of Automated Vehicle Occupancy Verification: California PATH	*173*

Chan and Wang (*173*) compiled information for a variety of facilities; that information is summarized below.

- For the I-10 and I-110 ExpressLanes in Los Angeles, California: The California Highway Patrol currently provides enforcement of the HOV lanes, on a randomized basis. Metro was expected to pay $500,000 per year for four patrols during the peak hours. The officers had limited or no shoulder throughout both corridors, though strategic zones for enforcement have been planned. CHP was responsible for toll and occupancy enforcement. The ExpressLanes used ALPR to assist in the enforcement of toll violations. The system serves as a backup to CHP and will read the license plate of vehicles without a transponder and subsequently determine if the vehicle's account is in good standing. Metro is currently considering which type of handheld devices will be helpful to CHP in verifying toll payments.
- For the I-495 Express Lanes in Northern Virginia: The Virginia State Police pays for the enforcement of the HOV lane occupancy requirements, collecting fines for traffic violations. The enforcement system currently depends on manual enforcement by the Virginia Department of Transportation (VDOT), but there is an expectation for automatic enforcement as a long-term strategy. In fact, the terms of the agreement with the concessionaire specify that an automatic enforcement system must be in place within 5 to 10 years. Occupancy violation will be enforced by visual inspection.
- For the METRO HOT Lanes in Houston, Texas: The METRO HOT lane violation enforcement strategy centers on the use of self-declaration lanes. At tolling locations, the single reversible lane diverges into two lanes: one lane designated for SOV users and the other lane for HOV users. An ALPR system is used to enforce SOV toll violations; highway patrol personnel do not need to intercept SOV toll violators. The license plate photograph taken by the ALPR system will be used to send a violation notice to the vehicle owner.
- For the I-25 HOV Express Lanes in Denver, Colorado: The self-declaration lanes and the ALPR system allow the patrol officers to concentrate on the HOV lane only. The task of the officer is to inspect the level of occupancy in the HOV. Colorado Department of Transportation (CDOT) pays the full cost at an overtime rate of $75 per hour. One officer patrols the lanes for 50 percent of the peak time periods (approximately 20 hours). CDOT has plans to provide handheld devices to assist the patrol officers. The E-470 Public Highway Authority is responsible for the operations of the ALPR system. On average, two cameras per lane capture front and back images of vehicles. A total of eight images are taken: two are infrared images and six are visible light images.
- For the MnPass Lanes in Minnesota: MnDOT funds two state patrol shifts: one shift from 6:00 a.m. to 10:00 a.m. and the other from 2:00 p.m. to 7:00 p.m. This is a supplemental service to the standard service provided by the state patrol. Additional enforcement is provided by city police and Metro Transit police. The officers use handheld devices to verify toll payment and whether a transponder was read. The enforcement of toll violations and occupancy violations is done entirely by the patrol officers due to a ruling by the state's Supreme Court banning the use of video tolling.

Impact on Operations

Table 81 lists the key reference for this subtopic. Related literature on this topic can be found in Table 79.

Table 81. Key reference for impact on operations.

Reference	Num
Katy Freeway: An Evaluation of a Second-Generation Managed Lanes Project	*127*

Incident Management

Multiagency Cooperation

No information on this subtopic was found in the literature.

Public Notification

No information on this subtopic was found in the literature.

Incident Response Protocol

No information on this subtopic was found in the literature.

Interim Use

Construction

No information on this subtopic was found in the literature.

Special Events

No information on this subtopic was found in the literature.

Emergency/Natural Disaster Use

No information on this subtopic was found in the literature.

Performance Monitoring and Evaluation

Table 82 lists the key references for this topic.

Table 82. Key references for performance monitoring and evaluation.

Reference	Num
Evaluating Criteria for Adapting HOV Lanes to HOT Lanes: Development and Application of HOT START Software Tool	*54*
Operational Performance Management of Priced Facilities	*64*
Performance Evaluation of I-394 MnPASS Express Lanes in Minnesota	*87*
Freeway Performance Measurement System (PeMS)	*183*
Toward the Evaluation of Value Pricing	*184*
Monitoring and Evaluating Managed Lane Facility Performance	*185*
Evaluation Framework for High-Occupancy-Toll Lanes	*186*
An Analytical Framework for Managed Lane Facility Performance Evaluation	*187*
HOV Performance Monitoring, Evaluation, and Reporting Handbook	*188*
Deterministic Approach to Managed Lane Analysis on Freeways in Context of Highway Capacity Manual	*189*

Performance Measures

Specific literature on this subtopic can be found in Table 82.

The performance measures used in the assessment of the I-394 MnPass Lanes include the following: speeds and travel time reliability, vehicle volumes, person throughput, number of transactions, transponder leases, revenue generation, and user satisfaction (*87*).

Data Needs

Specific literature on this subtopic can be found in Table 82.

Monitoring and Evaluation

Specific literature on this subtopic can be found in Table 82.

Reporting

Specific literature on this subtopic can be found in Table 82.

Evaluation Tools

Table 83 lists the key reference for this subtopic.

Table 83. Key reference for evaluation tools.

Reference	Num
Deterministic Approach to Managed Lane Analysis on Freeways in Context of Highway Capacity Manual	*189*

A recent research paper (*189*) documented an attempt to construct an approach to assess the performance of managed lane facilities within the context of the *Highway Capacity Manual*. A methodology was presented for estimating the performance of a parallel system of general-

purpose and managed lane facilities in an HCM context based on NCHRP Project 3-96. The methodology defines new managed lane segment types to use in an HCM analytical framework and is associated with a new set of speed-flow curves. It is sensitive to the number of lanes and the type of separation between managed lanes and general-purpose lanes. The method introduces the concept of parallel lane groups of general-purpose and managed lanes and thus can account for speed reduction in managed lanes caused by congestion in adjacent general-purpose lanes. The method was implemented in a computational engine, FREEVAL-ML, which was built on the freeway facilities method in HCM 2010 but was updated to incorporate inputs and outputs of the managed lane components. The geometry of two existing managed lane facilities in Washington State is used to illustrate the method, demonstrating the applicability of the analytical framework to real-world facilities.

Maintenance

Preventive Maintenance/Scheduled Closures

No information on this subtopic was found in the literature.

Response and Repair Requirements

No information on this subtopic was found in the literature.

System Availability

No information on this subtopic was found in the literature.

Winter

No information on this subtopic was found in the literature.

Tolling and ITS Equipment

No information on this subtopic was found in the literature.

Enforcement Areas

No information on this subtopic was found in the literature.

Emergency Pullouts

No information on this subtopic was found in the literature.

Pylons and Other Separation Hardware

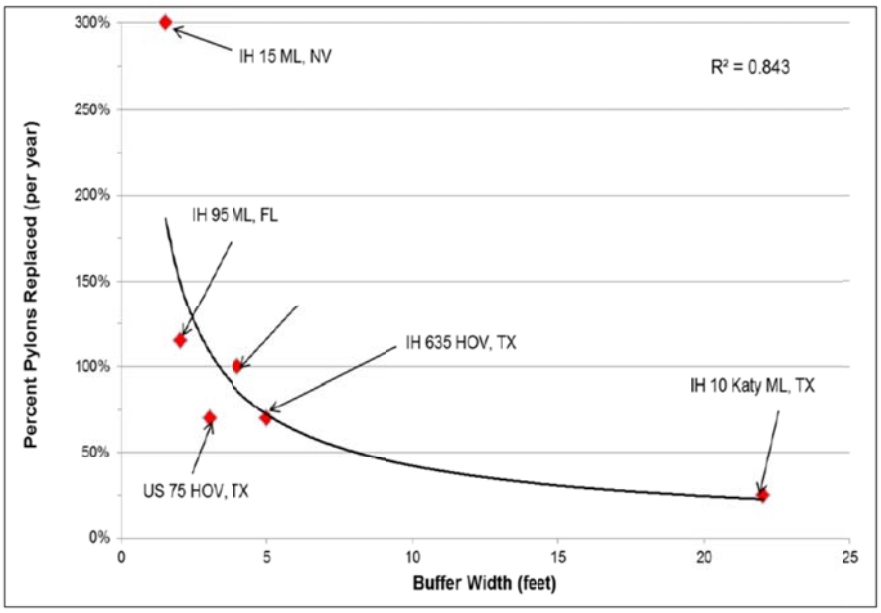
Table 84 lists the key references for this subtopic.

Table 84. Key references for pylons and other separation hardware.

Reference	Num
Best Practices: Separation Devices between Toll Lanes and Free Lanes	*122*
Guidelines for the Effective Use of Flexible Pylons for Congestion Mitigation, Access Management, and Safety Improvement	*190*

Researchers conducted a state-of-the-practice review and did vendor interviews on flexible pylons on behalf of the Texas Department of Transportation (*190*). A major focus of the research was on the use of pylons for managed lanes. Controlled experiments tested driver reactions with various speeds and different spaces between the pylons. Surveys were sent to agencies in the Houston, Dallas, and San Antonio regions. Researchers found, in their literature review, very little specific guidance for pylon design or use. Some guidelines regarding the color and retro-reflectivity of channelizing devices could be inferred from Sections 3H and 6F of the *Manual on Uniform Control Devices*. From the agency surveys, a majority of users indicated that they had issues with pylon replacement or pylons getting dirty and losing their target value, and they attributed hit and missing pylons to driver disregard and inattention. The case studies showed that a majority of the hits at all locations were intentional and involved light vehicles such as sedans, SUVs, and pickup trucks.

Researchers recommended a minimum of 10-ft spacing near the entry and exit access locations on managed lanes. It is the first few pylons that are hit most at access locations on managed lanes. The relationship between buffer width and pylon replacement per year is shown in Figure 46. A life-cycle cost comparison between pylons and center median barriers revealed that both deployments can be cost effective but are highly dependent on buffer width and right of way (*190*).



Source: (*190*)

Figure 46. Buffer width versus pylons replacement per year.

ADDITIONAL LITERATURE

There were additional academic articles that were reviewed by the research team but were not applicable to the outline proposed in the initial work plan. These include documents that focused on factors influencing travel behavior (e.g., such as willingness to pay), public perception impacts, overall air quality effects, and equity concerns that may be useful in an academic setting but may not be as critical to practitioners. For example, a large volume of the research focused on dynamic toll-setting models that were proposed for priced managed lanes but were not actually implemented. Additionally, there have been studies that have proposed various tools, but those tools were also not used or implemented by the respective agencies. Articles reviewed but not referenced earlier in this chapter include:

- S. Hess, E.R. Greene, C.S. Falzarano, and M. Muriello. 2011. "Pay to Drive in My Bus Lane: A Stated Choice Analysis for the Proposed Lincoln Tunnel HOT Lane Into Manhattan." *Transport Policy*, Vol. 18, No. 5, pp. 649–656.
- M. Aron, R. Seidowsky, and S. Cohen. 2013. "Safety Impact of Using the Hard Shoulder During Congested Traffic: The Case of a Managed Lane Operation on a French Urban Motorway." *Transportation Research Part C: Emerging Technologies*, Vol. 28, pp. 168–180.
- E.L. Duncan and M.J. Snyder. 2013. *Managed Motorways: Traffic Optimization and Road Pricing Approaches in Europe and Singapore*. Nova Science Publishers, Hauppauge, New York.
- A.Y. Bigazzi and M. Figliozzi. 2013. "Study of Emissions Benefits of Commercial Vehicle Lane Management Strategies." Presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, DC.
- K.T. Turnbull, K. Buckeye, and N. Thompson. 2013. "I-35W South MnPass High-Occupancy-Toll Lanes." Presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, DC.
- N. Bhouri and M. Aron. 2013. "Reliability Benefits of Active Traffic Management: Managed Lanes Case on French Urban Motorway." Presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, DC.
- N. Bhouri, M. Aron, and J. Kauppila. 2012. "Relevance of Travel Time Reliability Indicators: A Managed Lanes Case Study." Presented at the 15th Meeting of the EURO Working Group on Transportation, Paris, France.

APPENDIX B

ONLINE STATE AND LOCAL DOCUMENTS REVIEW

INTRODUCTION

As part of Task 2 efforts on NCHRP Project 15-49, the research team conducted a review of current policies, guidelines, and other documents in use by agencies that operate managed lanes. Identifying the state of the practice requires familiarity beyond the national guidelines and standards. Agency manuals and guidance documents also provide useful insight into the many aspects of implementing managed lanes. Rather than attempting to review documents from every agency in the United States, the research team chose 16 state, regional, and local agencies for this review; these agencies are considered to be among the leaders and innovators in managed lanes. The selected agencies, and their respective policy documents that were reviewed in this task, are as follows:

- California Department of Transportation.
  - *High-Occupancy Vehicle Guidelines for Planning, Design, and Operations* (*5*).
  - *Highway Design Manual* (*191*).
  - *California Manual on Uniform Traffic Control Devices* (*192*).
- Colorado Department of Transportation.
  - *I-25 Express Lanes FY 2013 4th Quarter Performance Report* (*193*).
- Florida Department of Transportation.
  - *Traffic Engineering Manual* (*194*).
  - *Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways* (Florida Greenbook) (*195*).
  - *Turnpike Plans Preparation and Practices Handbook* (*196*).
- Georgia Department of Transportation (GDOT).
  - *Design Policy Manual* (*197*).
- Los Angeles County Metropolitan Transportation Authority (LA Metro).
  - *HOV Performance Program Evaluation Report* (*198*).
- Maricopa Association of Governments.
  - *High-Occupancy Lanes and Value Lanes Study Final Report* (*199*).
- Maryland Transportation Authority (MdTA).
  - *Guidelines for "Express Toll Lane" Signing on Managed Lanes/Managed Facilities* (*200*).
- Minnesota Department of Transportation.
  - *Road Design Manual* (*201*).
  - *Minnesota Manual on Uniform Traffic Control Devices* (*202*).
- Nevada Department of Transportation.
  - *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*).
  - *HOV/Managed Lanes and Ramp Metering Public Outreach Primer* (*204*).
  - *HOV/Managed Lanes and Ramp Metering Implementation Plan* (*205*).
  - *HOV/Managed Lanes and Ramp Metering Design Manual* (*4*).

- North Central Texas Council of Governments (NCTCOG) Regional Transportation Council.
    - *Business Terms for TxDOT-Sponsored Toll Roads on State Highways* (*206*).
    - *Express Lane/HOV Lane Policies* (*207*).
    - *Policy on Excess Toll Revenue Sharing* (*208*).
    - *Policy on Excess Toll Revenue Sharing for Managed Lanes* (*209*).
    - *RTC Position Regarding Local Government and Transportation Provider Input* (*210*).
    - *Tolled Managed Lane Policies* (*211*).
- Tennessee Department of Transportation.
    - *Roadway Design Standard Drawings* (*212*).
    - *Traffic Design Manual* (*213*).
- Texas Department of Transportation.
    - *Roadway Design Manual* (*214*).
    - *Texas Manual on Uniform Traffic Control Devices* (*215*).
- San Diego Association of Governments.
    - *I-15 Managed Lanes Operations and Traffic Incident Management Plans* (*216*).
    - I-15 ML ETC System Concept of Operations (*217*).
- Santa Clara Valley Transportation Authority (VTA).
    - *High-Occupancy Toll (HOT) Network Implementation Principles* (*218*).
    - *Silicon Valley Express Lanes Program Implementation Assessment and Plan* (*219*).
    - *VTA Highway Program Semi-Annual Report* (*220*).
    - *VTA Transportation Handbook* (*221*).
- Virginia Department of Transportation.
    - *Amended and Restated Comprehensive Agreement Relating to the Route 495 HOT Lanes in Virginia Project* (*222*).
- Washington State Department of Transportation.
    - *Design Manual* (*29*).
    - *Traffic Manual* (*223*).

The reviewed documents are those that were available to the general public through the agencies' websites; while these agencies may have other relevant documents in use for managed lane implementation, documents not found online were not included in this review. The documents reviewed contain guidance or policy statements on a wide variety of topics related to the planning, design, implementation, and operation of managed lanes. The information from those documents is summarized by topic in the following sections; topics are presented in this chapter to correspond to the outline of the draft guidelines that were prepared during Task 3. Some of the reviewed documents contained information on multiple topics, and the summaries provided in this chapter indicate the key topics of interest. For some topics, no documents were found that contained applicable information or the relevant documents are referenced under other topics. Where no information was found for a particular topic, it is noted in that section of the outline.

PLANNING CONSIDERATIONS

Planning and Programming

Needs, Goals, and Objectives Identification

VTA's Board of Directors approved a set of HOT lane network implementation principles (*218*) to establish guidance for development of the system, define the system's objectives, and present a structure for collaboration and cooperation among many stakeholder agencies. The agency also conducted an implementation assessment (*219*) to help guide its planning of the Silicon Valley Express Lanes Program.

Maricopa Association of Governments conducted a wide-ranging study to evaluate the need for managed lanes in the Phoenix area. The resulting report (*199*) provides recommendations for lanes on individual freeways, locations and designs of specific access points, financial and operational evaluations, demand management and enforcement needs, and implementation strategies.

Caltrans (*5*) has several factors and criteria related to HOV system planning. An HOV proposal must be consistent with existing strategies and priorities for district congestion management, air quality management, and regional transportation plans. If those criteria are met, the HOV proposal must be able to:

- Meet highway design guidelines.
- Maintain highway safety.
- Meet requirements for anticipated demand.
- Be cost effective.
- Meet requirements for travel time savings.
- Enforce violations easily and safely.
- Use other elements (e.g., park-and-ride facilities, public awareness campaigns) to support its success.

Nevada DOT (*203*) has criteria to justify the creation of a particular HOV or managed lane. The criteria, based on the anticipated demand volume, vary by the type of facility, typically established between 250 and 700 vph directionally in the opening year for a line-haul treatment, adapting a figure from the AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*), as shown in Table 85.

NDOT (*205*) recommends both regional and corridor-level planning. Its guidelines state that an implicit set of conditions must exist for HOV or any other form of managed lanes to be considered viable; those conditions include the following:

- *Congestion*. A recurring congestion problem to LOS D or worse (defined as average speeds below 30 mph) within a corridor or region during the defined peak hours each weekday.
- *Limited resources*. A significant backlog of unmet travel demand and lack of available resources (right-of-way, funding, regional consensus, or environmental

issues) to address capacity deficiencies in a more conventional means through adding roadway or transit capacity.

- *Desire to promote mobility*. An interest and ability by agency stakeholders to minimally or incrementally increase roadway capacity by managing its use to specific dedicated purposes to ensure that a high level of service can be provided as an alternative to recurring congestion for at least some users. The public must support this approach.

Table 85. Vehicle volume operating thresholds for freeway managed lanes in Nevada.

Facility Type	Vehicle Volume Threshold (vehicles/lane/hour)		
	Minimum (opening year)	Minimum (design year)	Maximum
Barrier-separated, one or two lanes each direction	700	1000	1650–1800
Barrier-separated, reversible flow, one or two lanes	700	1000	1650–1800
Concurrent-flow (not physically separated), one or two lanes each direction	500	1000	1650–1800
HOV direct-access ramp at an interchange	200	1000	Depends on downstream merge volumes
HOV ramp meter bypass	Not applicable	Typically 100–200	Not applicable

Source: (*203*).

A list of possible goals and objectives for the implementation of managed lanes is reproduced in Table 86.

WSDOT (*29*) states that a viable HOV facility satisfies the following criteria:

- It is part of an overall transportation plan.
- It has the support of the community and public.
- It responds to demonstrated congestion or near-term anticipated congestion: LOS E or F for at least one hour of peak period (traffic approaching a capacity of 1700 to 2000 vphpl) or average speeds less than 30 mph during peak periods over an extended distance.
- Except for a bypass of a local bottleneck, it is of sufficient length to provide a travel time saving of at least five minutes during the peak periods.
- It has sufficient numbers of HOV users for a cost-effective facility and avoids the perception of underutilization (HOV volumes of 400 to 500 vph on non-separated lanes and 600 to 800 on separated facilities).
- It provides a safe, efficient, and enforceable operation.

In order to determine the appropriate design options for an HOV facility, the agency must establish the travel demand and capacity, identify suitable corridors, evaluate the HOV facility location and length, and estimate the HOV demand.

Table 86. Examples of goals and objectives for managed lane facilities.

Goals	Objectives
• Maintaining or improving mobility • Improving roadway operation efficiency and reliability • Promoting transit and ridesharing • Addressing environmental considerations and adopted land uses • Enhancing air quality (compared to no-build and conventional build alternatives) • Maintaining safety • Providing travel options to meet user needs, such as time-sensitive travel • Addressing economic and financial considerations	• Increasing person-moving capacity of the roadway • Promoting transit and ridesharing mode split • Optimizing vehicle-carrying capacity • Promoting travel time savings, reliability, or efficiency for selected travel modes • Promoting air quality by increasing ridesharing and transit as part of a conformity plan • Increasing funding opportunities for new mobility improvements by generating revenue to offset capital and operating expenses • Enhancing existing transit investments and services in the region/corridor • Providing a greater choice in serving multimodal needs (people, goods, services) • Improving the movement of commerce (goods and services movements) • Supporting community land use and development goals, particularly to major areas of employment

Source: (*203*).

Intended Customers/Markets

Nevada's *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*) describes the primary users for HOV and managed lanes as buses, vanpools, and carpools; the default eligibility to any HOV lane is two or more persons per vehicle. Managed actions, including the potential of raising occupancy requirements, will be considered whenever LOS C (30 mph) is degraded during the peak hours. Degradation will be considered when 25 percent of the time the peak hours fall below this threshold.

Strategy Selection and Operational Approach

Corridor and project planning addresses what type of HOV or managed lane would be appropriate and how it should be designed, implemented, and operated. To address these questions, studies involve a greater level of detail. Corridor planning examines how the HOV improvement is best developed into projects and programmed to take advantage of opportunities while minimizing impacts to traffic. At this level, more comprehensive study is needed to review specific site conditions and operations, thus requiring more field design and operational data and input from affected agencies. Accordingly, criteria will be more quantitative and corridor specific. For example, demand will need to be explored from a variety of more detailed perspectives, including how much demand is related to transit, van and carpooling, where it is coming from (spatial or modal shifts), and what impacts it is creating to other modes or parallel and intercepting corridors). Nevada DOT (*205*) provides the following list of criteria as illustrative of the types of comparative factors that help guide a corridor-level planning effort. A design plan and an operational plan should be developed as a result of this corridor-level review.

- Congestion.

- Travel time savings.
- Travel reliability.
- Transit services and facilities.
- Demand.
- Access.
- Roadway and right-of-way characteristics.
- Environmental issues.
- Cost effectiveness.
- Financial viability.
- Enforceability.
- Phasing/constructability.
- Safety/incident management.
- Compatibility with other plans and services.
- Public and agency acceptance.
- Operational impacts.
- Local criteria.

Partnerships/Agreements

The North Central Texas Council of Governments has a defined statement (*210*) regarding input from local partners on transportation projects:

- The Regional Transportation Council requests input from local governments and transportation providers on all transportation planning, project development, and program implementation efforts.
- The Regional Transportation Council requests input from local governments on all toll pricing policies and institutional arrangements with transportation providers.
- The Regional Transportation Council will strongly consider the recommendations from local governments regarding specific transportation providers, considering the merits of the competing interests on funding, regional mobility, reliability, safety, air quality, and economic development.
- The Regional Transportation Council will mediate corridor-specific concerns if they are regional in nature.

Virginia (*222*) has a formal document describing the comprehensive agreement between the parties (VDOT and Capital Beltway Express, LLC) that developed the I-495 Express Lanes facility. The document provides details on the parties' roles and responsibilities, establishment of tolls, project financing, construction, project management, and contracting among the items required to formalize the partnership between the two parties to complete the I-495 Express Lanes.

Nevada DOT's *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*) describes recommended roles for NDOT, regional transportation commissions, cities, counties, transit agencies, and other partners in various tasks to accomplish planning, project development, operation, marketing, and performance monitoring. NDOT has the primary role for most planning tasks and project development, along with operational policy, outreach, and performance data collection. Regional commissions, cities, and counties play larger roles in

operations and marketing. The functional roles outlined serve as a means of establishing working relationships on projects or regional system task forces. Specific roles may be assigned on a project-by-project basis. In each case, the lead agency is charged with the responsibility of coordinating and communicating with partnering agencies and addressing issues of common interest and concern.

Funding and Finance

The North Central Texas Council of Governments has two defined statements on the appropriate use of excess toll revenue from its facilities; one applies to managed lanes (*209*), while the other is specific to TxDOT-sponsored toll facility projects (*208*) within the NCTCOG region. The key items in those policies are as follows:

- Excess toll revenue is defined as annual toll revenue after annual debt service, and after annual reserve funds have been set aside to cover facility operational costs; anticipated preventive maintenance activities; assigned profit and related expenses for the Comprehensive Development Agreement; and expected cost of rehabilitation or reconstruction of the managed toll lanes.
- All excess revenue generated from an individual managed lane toll project will remain in the county or TxDOT district in which that revenue-generating managed lane project is located.
- Local governments and transportation authorities will be given the right to invest in a Comprehensive Development Agreement project as a means to fund the facility as well as to generate local revenue.
- Excess revenue will be returned to the funding partners in proportion to their shares and be used to fund future transportation projects.
- Regional Transportation Council shares will be put in air-quality-related and sustainable development programs and used to leverage federal transportation funds.

Nevada DOT (*203*) states that it will be the primary designated agency to develop a funding plan for the regional HOV system and for individual projects, but securing funding for specific HOV projects will be a responsibility for all affected local agencies in each urban area. Local, state, and federal funding all play a role in making an HOV project and its related facilities feasible. With respect to potential federal transit funding, the local transit provider has the responsibility for Federal Transit Administration (FTA) funding, and NDOT has the responsibility for FHWA highway funding.

Concept of Operations

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, access to and from the managed lanes, signs and vehicle identification systems, and staged system implementation.

Policy and Legislative Considerations

NCTCOG has a variety of policy documents available to the public. Several are specific to a single topic, but its *Express Lane/HOV Lane Policies* (*207*) cover a variety of items from pricing to vehicle eligibility:

- A fixed-fee schedule will be applied with periodic adjustments to the rate schedule necessary to meet established speed guarantee. It is anticipated that these corridors will be instrumented with toll collection equipment in time to seamlessly interface with tolled managed lanes. Other tolling methods can be considered if seamless operation cannot be achieved in a timely fashion.
- The toll rate will be set, similar to the managed lane rate, up to $0.75 per mile. The established rate will be evaluated and adjusted, if warranted, with regional transportation council approval. It is anticipated the actual toll rate will be lower than this.
- Express lanes/HOV lanes will be enforced manually. Enhanced technology will be utilized when available and can be retrofitted in each corridor.
- Transit vehicles will not be charged a toll.
- Single-occupant vehicles will pay the full rate.
- Trucks will not be permitted due to inadequate design standards.
- Motorcycles qualify as high-occupancy vehicles and will not be charged a toll.
- No discount will be given to "green" vehicles.
- High-occupancy vehicles with two or more occupants and vanpools will be free at all times.
- When the available capacity of the express/HOV lane is full from HOV2+ users, additional options based on select data points may be considered for future occupancy requirements.
- The toll rate will be established to maintain a minimum average corridor speed of 50 mph.
- Rebates will not apply to express/HOV lanes since dynamic pricing will not be implemented.
- Every express lane/HOV lane corridor will operate under the same regional policy.
- Adoption of this policy will have no impact on the regional transportation council excess revenue policy previously adopted.

Pricing

NCTCOG (*211*) lists a series of specific items in its pricing policy for tolled managed lanes operated by the North Texas Tollway Authority. These items include the toll rate per mile and vehicle eligibility.

Nevada DOT's *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*) contains a more general list of items in determining pricing for a facility:

- Pricing may be considered on either an HOV or managed lane, either for a planned or operating project.

- Pricing will primarily be considered as a means of promoting more efficient traffic management and, accordingly, may be considered for selected hours and selected projects.
- Any pricing will involve electronic toll collection technology with vehicles/owners registered in advance and handled through off-line accounting. No toll booths will be implemented on HOV or managed lane facilities.
- Pricing, if implemented, will attempt to manage traffic in real time, or dynamically, by setting a price that either encourages or discourages use to manage flow at an operational threshold below the lane's capacity.
- Any consideration of pricing will be subject to the following studies or evaluations:
    - Evaluation of demand, impacts and benefits.
    - Evaluation of technology, enforcement, and institutional arrangements.
    - Revenue generation potential.
    - Public support through outreach.
    - A policy level determination to address any net excess revenue generated.
- No pricing approach will adversely impact the formation and promotion of transit and ridesharing in a corridor or the region.
- Consistency will be applied in pricing multiple facilities, in terms of pricing policy, administration, and technology.

Enforcement Approach

On Nevada's managed facilities (*203*), police staffing is increased during the initial months of a new project opening, as NDOT places an emphasis on having dedicated enforcement personnel during this period. Since staffing requirements will vary by type of project, length, and operation requirements, the respective police agency should provide assistance in the desired allocation of staff. Specific strategies for enforcement will be the responsibility of these police agencies.

Extraordinary enforcement funding (overtime pay or contracted support) for HOV and managed lane enforcement is considered as part of each new project opening, up to a period of six months. This practice is common in other areas, particularly on a region's first or second HOV lane project. This funding should be included as part of the overall project implementation budget. Typically, this budget is established by NDOT and approved by FHWA. After the opening period for a new project, funding is anticipated to be covered as a part of the typical traffic operations budget by the respective police agency(ies).

Violations and Adjudication

No information on this topic was found in an online manual or policy document.

Operational Changes

No information on this topic was found in an online manual or policy document.

Public Involvement and Outreach

Common Messages and Public Education

Nevada DOT discusses outreach target markets and key messages in its *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*). NDOT says that target markets include not only corridor users but also those in the position of setting and supporting transportation policies. By segmenting the messages sent to individual HOV/managed lane markets, education and promotion strategies that can turn those individual markets into users and/or supporters of the HOV/managed lane can be developed. HOV/managed lane target markets by segment include:

- Corridor users.
- Employers.
- Community/special interest groups.
- Elected officials.
- Enforcement officials and judges.
- Media (as a community leader and opinion shaper).

Table 87 describes NDOT's key messages to corridor users; NDOT provides similar tables for other target markets.

Project Champion

No information on this topic was found in an online manual or policy document.

Engaging Policy Makers

Aside from the information by NDOT (*203*), no information on this topic was found in an online manual or policy document.

Engaging the Media and General Public

Aside from the information described previously from NDOT (*203*), no information on this topic was found in an online manual or policy document.

Project Delivery and System Integration

No information on this topic was found in an online manual or policy document.

Table 87. Key messages conveying HOV/managed lane benefits for corridor users.

Key Messages	Communication Mechanism	Desired Outcome
• Provision for current and future mobility. • Immediate travel time savings for HOV/managed lane users. • Predictable travel time for HOV/managed lane users. • Less stress for HOV/ managed lane users. • Incentive for commuters to make a carpool/vanpool/ transit choice. • Enforcement to ensure equity and fairness for users and nonusers. • Accurate and detailed information on what HOV/managed lanes can (and cannot) accomplish for the region.	• Print and broadcast news media relations. • Project brochure distribution via requests and point-of-purchase displays. • Desktop distribution of brochure at area worksites. • Emphasis of website as mechanism to get information about project specifics and HOV/ managed lane in general. Link to website for ridesharing and transit information. • Information distribution as part of publicly sponsored transportation fairs. • Information distribution at gathering spots—malls, festivals, etc. • Newspaper advertisements.	• Awareness that HOV/ managed lane facilities are an important element in providing travelers transportation choices. • Positive anticipation of the HOV/managed lane opening. • Motivation to call for transit/rideshare information. • Understanding that HOV/managed lane facilities are a prudent use of limited funds and scarce land. • Familiarity with HOV/managed lane operational rules and benefits. • Awareness that violators will be prosecuted to full extent of the law.

Source: (*203*).

Interoperability/Regional Consistency

No information on this topic was found in an online manual or policy document.

Federal and State Environmental Requirements and Permitting

No information on this topic was found in an online manual or policy document.

Decision-Making Process on Management Strategy and Managed Lane Facility Type

Caltrans (*5*) and NDOT (*205*) describe specific modes of HOV lane operation (e.g., two-way flow, reversible flow, and contraflow) and when they are most appropriate. Hours of operation, vehicle occupancy, and vehicle type are also included in the discussions.

Forecasting/Traffic Analysis

No information on this topic was found in an online manual or policy document.

DESIGN ELEMENTS

Safety Performance

No information on this topic was found in an online manual or policy document.

General Geometric Design Considerations

Design and Operational Consistency Across Local, Regional, and National Systems

Some states, rather than describing their own criteria for managed lanes, refer to other existing policies. For example, the TxDOT *Roadway Design Manual* (*214*) refers the designer to AASHTO's *Guide for the Design of High-Occupancy-Vehicle Facilities* (*3*) and NCHRP Report 414 (*38*) for guidelines for the planning and designs of HOV facilities. Caltrans HOV guidelines (*5*) make reference to the Caltrans *Highway Design Manual* (*191*).

Design Vehicle/Eligibility

Nevada DOT (*4*) states that design vehicles for HOV and managed lanes are essentially the same as for general-use freeway lanes. The physical and operating characteristics of users will influence the design of the managed lane. Listed in Table 88 are generalized requirements associated with typical design vehicles. Motorcycles, hybrid powered vehicles, and emergency vehicles also commonly receive consideration on managed lane facilities.

Table 88. Sample design vehicle dimensions.

Design Vehicle Type	Height (ft)	Body Width (ft)	Length (ft)	Overhang (ft)		Wheelbase (ft)
				Front	Rear	
Passenger Car	4.25	7.0	19	3.0	5.0	11.0
40-ft City Bus	10.5	8.5	40	7.0	8.0	25.0
45-ft Bus	12.0	8.5	45	6.0	8.5	26.5
Articulated Bus	11.0	8.5	60	8.6	10.0	22.0 front, 19.4 rear

Source: (*4*).

It is WSDOT policy (*223*) to use the 2+ designation as the initial occupancy designation for an HOV lane. WSDOT considers a 3+ occupancy designation if it is anticipated during initial operation that the volumes will be 1500 vph for a left-side HOV lane, or 1200 vph for a right-side HOV lane, or that a 45-mph operating speed cannot be maintained for more than 90 percent of the peak hour.

Managed Lane Facility

NDOT's *Managed Lanes and Ramp Metering Design Manual* (*4*) states that HOV and managed lanes should generally meet requirements for urban freeway lanes as specified in the NDOT *Project Design Development Manual*. NDOT uses tables from the AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*) for guidance for mainline and ramp treatments; the table for freeway mainline criteria is reproduced as Table 89.

Managed Lane Placement with Respect to Mainlanes

In Nevada (*4*), freeway HOV/managed lanes are typically located adjacent to the median to avoid conflicts with local ramps and associated merging with local access ramps. Median orientations are also more amenable to limiting HOV lane ingress and egress and discouraging shorter-distance trips from using the HOV lane. Median-oriented breakdown shoulders are typically used by HOVs, and right-side shoulders are used by general traffic. However, most concurrent HOV lanes would permit traffic from either roadway to use whatever shoulder is most convenient, even if access restrictions exist between the HOV and general-purpose lanes.

Median-oriented HOV lanes do not work well for transit services that require frequent loading and unloading of passengers because buses can spend more effort merging into and out of the dedicated lane than benefiting from it. Median bus stations should be considered for this type of service and lane orientation, or the transit service plan should be tailored to more point-to-point express non-stop service that does not require intermediate stops.

Outside-shoulder HOV lane treatments on freeways are not suitable to a heavy volume of mixed buses and carpools. Such treatments can be workable for short distances to serve as a bus queue bypass between successive local access ramps, and for temporary settings where transit stops may already be in existence. A facility in the Seattle area has relocated right-side HOV lanes to the median as demand has grown (see Figure 47) (*4*). Borrowing an inside shoulder for high-speed HOV lane traffic is not encouraged because the temporary use of a breakdown shoulder for a moving lane can confuse motorists. Outside shoulder use should be clearly signed, speeds should be reduced for shoulder users, and conditions should be closely monitored.

Table 89. Summary of HOV/managed lane mainlanes criteria.

Design Parameter	Ramp Condition
Design Speed	In urban areas, a design speed of 70 mph is desirable when the corridor of the mainline is relatively straight and when the character of the roadway and the location of interchanges permit high speeds. Minimum design speed should not be less than 50 mph.
Stopping Sight Distance (on level roadway)	At 70 mph, the minimum stopping sight distance needed is 730 ft. At 50 mph, the minimum stopping sight distance needed is 425 ft.
Horizontal Alignment	
Radius of Horizontal Curvature	The radius of horizontal curvature used in a particular roadway design is a function of the design speed, rate of superelevation, and side friction with practical limits due to ROW constraints. As the design speed increases and the rate of superelevation decreases, the minimum radius of horizontal curvature required increases. In an urban environment with a maximum rate of superelevation (e_{max}) of 4% to 6%, the minimum radius at 70-mph design speed is 2050 ft at e_{max} = 6% to 2345 ft at e_{max} = 4%. At 50-mph design speed, minimum radius is 835 ft at e_{max} = 6% to 930 ft at e_{max} = 4%.
Superelevation	The rate of superelevation used in a particular roadway design will be a function of the design speed, radius of curvature, and side friction with practical limits based on driver comfort, safety, climate, and local agency standards. As design speed increases and the radius of curve decreases, the need for superelevation increases. AASHTO specifies that in an urban environment, a maximum superelevation rate of 4% to 6% is common practice.
Vertical Alignment	
Rate of Vertical Curvature, K-Crest	Basing the minimum lengths of crest vertical curves (and the rate of vertical curvature) on stopping sight distance criteria is usually sufficient from the viewpoint of safety, comfort, and appearance. In some instances, decision sight distance criteria should be considered. Based on stopping sight distance at 70-mph design speed, the minimum K = 247. At 50-mph design speed, the minimum K = 84.
Rate of Vertical Curvature, K-Sag	The use of stopping sight distance criteria for establishing minimum rates of vertical curvature is recommended. However, three other criteria are evaluated when designing a sag vertical curve, namely passenger comfort, drainage control, and general appearance. At 70-mph design speed, the minimum K = 181. At 50-mph design speed, the minimum K = 96.
Alignment Combined	Horizontal and vertical alignment should not be designed independently. See AASHTO *Green Book*, Chapter 3, Elements of Design.
Grades	Maximum grades for 50-mph design speed on level or rolling terrain are 4% and 5%, respectively. For 70-mph design speed, maximum grades are 3% and 4%, respectively. Length of grade and design vehicle are important to consider. When the cross slope of the road is sufficient to drain the pavement surface adequately, flat grades can generally be used without a problem.
Clearance—Vertical	Desirable is 16 ft, and where this minimum vertical clearance would be cost prohibitive in highly urbanized areas, a minimum clearance of 14 ft may be used if there is an alternate freeway facility with the minimum 16-ft clearance. Allowance should be made for future resurfacing.
Clearance—Horizontal	See AASHTO *Roadside Design Guide*.
Lane Width	HOV lane widths should be 12 ft.
Cross Slope	Minimum: 1.5% to 2%. Maximum: 2% to 2.5% (center crown).

Source: (*4*).

Source: (*4*)

Figure 47. I-405 HOV lane before and after conversion to inside HOV orientation in Seattle area.

Separation Between Managed Lane and Mainlanes

NDOT (*4*) and Caltrans (*5*) provide descriptions of various types of separation treatments (e.g., buffer, barrier, none) and describe selected situations for which some treatments are preferred over others. A selection of typical cross-sections is also provided in their guidance documents.

General conclusions from NDOT (*4*) and Caltrans (*5*) are that some form of delineation is needed for any kind of concurrent-flow lane to differentiate it from adjacent lanes. At a minimum, separation needs to be a pavement marking that is wider than standard. If a managed lane restriction is applied on a part-time basis and the lane reverts to general use at other times, then the lane should not be so differentiated that it causes motorist confusion during non-restricted periods. However, for full-time operations, some additional form of separation is encouraged. Painted buffers or provision of physical separation promote more efficient traffic flow where travel speed differentials in adjacent lanes can be quite high, and these treatments may improve operational safety. Managed lanes employing pricing may need some form of physical separation (e.g., hard concrete barriers or soft pylon barriers) to deter toll evaders.

Access to Managed Lane

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, access to and from the managed lanes, signs and vehicle identification systems, and staged system implementation.

NDOT (*4*) and Caltrans (*5*) provide descriptions of various types of access configurations (e.g., transition, at-grade, direct) and describe selected situations for which one treatment is preferred over others.

Access consideration is needed for any design. As a minimum, design consideration is needed for how a lane transitions to and from adjacent general-purpose lanes. Access along a concurrent-flow lane may be allowed at any point, or access may be restricted. If access is restricted, designated access zones or direct-access ramps will be needed. If a reversible or contraflow lane is designed, all access features will need to be through designated access ramps to control the direction of traffic.

Transit Considerations

Guidance by Caltrans (*5*) and NDOT (*4*) includes provisions and design requirements for transit facilities in conjunction with managed lanes. The most common forms of transit treatment include stations and parking lots. Stations are either constructed separate from the freeway as off-line stations and may be connected through a drop ramp or flyover ramp, or constructed online in the freeway median straddling the HOV/managed lane facility. In all configurations, the main HOV/managed lane roadway operates around the station on separate, high-speed through lanes, so the station must be properly separated from the through lanes by barriers to minimize inadvertent entry by non-transit vehicles. Consideration must be given to providing adequate dwelling and queuing areas for buses, along with the ingress and egress paths of the buses when accessing the station. The design must also accommodate transit riders anticipated to use the facility, particularly those with additional mobility needs. The various manuals provide details of specific design features. Park-and-ride lots are typically accessed through direct-access ramps, which are designed similarly to direct-access ramps for other purposes.

Truck Considerations (Including Freight/Truck-Only Facilities)

No information on this topic was found in an online manual or policy document.

Issues Unique to HOV Lane Conversion

No information on this topic was found in an online manual or policy document.

Design Variances

No information on this topic was found in an online manual or policy document.

Flexible Design Philosophies

No information on this topic was found in an online manual or policy document.

System Integration Considerations

No information on this topic was found in an online manual or policy document.

Operational Impacts on Design

Operational Strategy's Impact on Design

No information on this topic was found in an online manual or policy document.

Tolling Systems

Florida (*196*) has specific requirements for the provision of tolling infrastructure and toll plaza design. This infrastructure includes but is not limited to toll equipment structures (gantries), structural support members for horizontal pipes, horizontal support pipes, toll equipment arms (j-arms), toll equipment arm attachment hardware, existing toll plaza canopy modifications if required, full-depth asphalt pavement or fiber-reinforced concrete pavement under the gantry, NEMA enclosures, concrete pads, directional bores, underground duct banks, wireways, pullboxes, conduits, new toll equipment support buildings, modifications to existing toll equipment support buildings and tunnels, building/tunnel penetrations, maintenance access, generators, fuel storage tanks, uninterruptable power supplies, communications, utilities, mechanical, plumbing, electrical, and ITS. Descriptions and details of provision for these and other related items are described in the *Turnpike Plans Preparation and Practices Handbook* (*196*).

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, signs and vehicle identification systems, and staged system implementation.

Enforcement Systems

HOV lanes should be designed so that they can be safely and efficiently enforced. The safety of both police personnel and travelers in the HOV lane and the general-purpose lanes should be considerations in the design process. In addition, local or state laws regarding enforcement policies and practices should be considered with enforcement agency input. Project success is jeopardized by enforcement areas or provisions that will not be used by the respective police. Some lane treatments such as reversible lanes are relatively easy to enforce because of the limited ingress and egress opportunities. Other design treatments are much more difficult because they share common pavement with other traffic. Table 90 highlights some of the attributes associated with HOV lane enforcement strategies in Nevada. Barrier-separated lanes are generally considered to be easier to enforce than non-separated facilities because of the limited and controlled access they provide. Details on recommended designs of enforcement systems are provided in the manuals from Nevada and Washington (*4*, *6*).

Caltrans (*5*) provides several enforcement alternatives including wide paved median shoulders and directional or bi-directional enforcement areas. Median width and buffer type are discussed in the context of enforcement, and a selection of typical cross-sections is provided.

Table 90. Enforcement attributes associated with different HOV facilities.

Type of HOV Lane Facility	Preferred Enforcement Attributes	Minimum Enforcement Attributes
Concurrent-Flow Barrier-Separated: Two-Way and Reversible	Enforcement areas at entrances and 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 right-side shoulders	Enforcement area at entrance
Queue Bypass Treatments	Enforcement area on right-side shoulder Continuous right-side shoulder Duplicate signal head facing enforcement area	Enforcement monitoring pad with continuous right-side shoulder downstream

Source: (*4*).

Capacity

No information on this topic was found in an online manual or policy document.

Traffic Control Devices

Traffic Control Device Requirements for Specific Operations

No information on this topic was found in an online manual or policy document.

Static Signs

Recommendations for signing typically repeat or refer to the applicable text and figures found in the most recent version of the federal MUTCD or state equivalent (*4*, *194*, *213*).

The California MUTCD (*192*), Texas MUTCD (*215*), and Minnesota MUTCD (*202*) contain Chapter 2F on toll road signs and Chapter 2G on signs for preferential and managed lanes, similar to Chapters 2F and 2G in the federal MUTCD. The Caltrans HOV guidelines (*5*) describe recommended signs and markings in conjunction with the principles contained in the federal MUTCD and the California MUTCD (*192*).

Maryland has guidelines (*200*) for signage on its managed lane facilities. The guidelines reference the federal MUTCD and other documents for support. Tennessee has a standard drawing (*212*) within its roadway design guidelines that describes the typical sign layout for HOV lanes.

Dynamic Message Signs

The California MUTCD (*192*), Texas MUTCD (*215*), and Minnesota MUTCD (*202*) contain information on changeable message signs in Chapter 2L, similar to Chapter 2L in the federal

MUTCD, but no information on this topic specific to managed lanes was found in an online manual or policy document.

Maryland has guidelines (*200*) for signage on its managed lane facilities. The guidelines reference the federal MUTCD and other documents for support.

Lane Control Signals

The California MUTCD (*192*), Texas MUTCD (*215*), and Minnesota MUTCD (*202*) contain information on lane-use control signals in Chapter 4M, similar to Chapter 4M in the federal MUTCD.

Pavement Markings

Recommendations for markings typically repeat or refer to the applicable text and figures found in the most recent version of the MUTCD or state equivalent (*4*, *194, 213*).

The California MUTCD (*192*), Texas MUTCD (*215*), and Minnesota MUTCD (*202*) contain information on markings for managed and preferential lanes in Chapter 3D, similar to Chapter 3D in the federal MUTCD.

The Caltrans HOV guidelines (*5*) describe recommended signs and markings in conjunction with the principles contained in the federal MUTCD and the California supplement to the MUTCD.

Tennessee has a standard drawing (*212*) within its roadway design guidelines that describes the typical markings for HOV lanes.

Other Methods of Disseminating Information

No information on this topic was found in an online manual or policy document.

IMPLEMENTATION AND DEPLOYMENT

Project Implementation

Design Review

No information on this topic was found in an online manual or policy document.

Schedule/Installation

No information on this topic was found in an online manual or policy document.

Testing and System Acceptance

No information on this topic was found in an online manual or policy document.

Project Deployment

Project Delivery

No information on this topic was found in an online manual or policy document.

Outreach and Marketing

No information on this topic was found in an online manual or policy document, other than the information on public involvement and outreach previously summarized.

Tolling Deployment

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, signs and vehicle identification systems, and staged system implementation.

System Phasing and Development Considerations

No information on this topic was found in an online manual or policy document.

Coordination

Utilities/Cities

No information on this topic was found in an online manual or policy document, other than the information on partnerships and agreements previously summarized.

Construction Coordination/Phasing

No information on this topic was found in an online manual or policy document.

Upgrades and Expansions

No information on this topic was found in an online manual or policy document.

OPERATIONS AND MAINTENANCE

General Operations Issues

Pricing

Specific treatments for pricing management relate to the need to substantially segregate managed lanes from adjacent free lanes, provide communication to toll users, and enforce and administer the tolling process. While many options exist to address these needs, previous

experience in Nevada (*4*) suggests that the most appropriate options involve the following features:

- Separation of the HOV lane by concrete barriers, traffic pylons, or channelizers, with limited access. Open, unrestricted access has yet to be successfully demonstrated without a need for very frequent toll reading installations.
- Toll collection performed at one or a limited number of locations along the managed lanes through one or more methods of electronic toll collection.
- Enforcement considerations for occupancy, toll, and ingress/egress violations.
- Signing located upstream of the entrance ramps to communicate the toll and its related benefits.
- An off-site facility or service that handles toll collection and administration.

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, signs and vehicle identification systems, and staged system implementation.

Operation Management

No information on this topic was found in an online manual or policy document.

Startup/Opening Guidelines

No information on this topic was found in an online manual or policy document.

Eligibility Validation (Manual and Automated)

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, signs and vehicle identification systems, and staged system implementation.

Traffic Monitor and Control

No information on this topic was found in an online manual or policy document.

Access Control and Safety

No information on this topic was found in an online manual or policy document.

Enforcement

Approaches

In Nevada (*203*) and California (*5*), the goal for occupancy compliance is 90 percent of the use of the HOV or managed lane. Establishing a standard for acceptable violation rates on a

particular facility should include safety considerations, freeway operations, public attitudes, and practicality.

Techniques, Tactics, and Technology

On Nevada's managed facilities (*203*), police staffing is increased during the initial months of a new project opening. Dedicated enforcement personnel during this period is a goal for any new project. Since staffing requirements will vary by type of project, length, and operation requirements, the respective police agency should provide assistance in the desired allocation of staff. Specific strategies for enforcement will be the responsibility of these police agencies. After a defined initial opening period, the goal of HOV and managed lane enforcement is to make it a part of other traffic and incident management duties, and not assign dedicated staffing to this function.

Impact on Operations

Caltrans (*5*) states that past studies suggest there is no consistent correlation between crash rates and occupancy violation rates on any of California's HOV facilities. However, the practice of weaving in and out of an HOV lane creates a safety issue for the violator as well as for other traffic. Many of California's HOV facilities are operating near capacity. As traffic flow approaches capacity, violations represent a threat to the time savings and other benefits of HOV facilities.

Incident Management

Multiagency Cooperation

No information on this topic was found in an online manual or policy document.

Public Notification

No information on this topic was found in an online manual or policy document.

Incident Response Protocol

SANDAG has a policy document (*216*) describing its traffic incident management plan, which includes a summary of other agencies' practices. The document describes a variety of scenarios that the agency must consider and potentially respond to in the event of a traffic incident.

Caltrans (*5*) describes prescribed methods for addressing incidents and special events on HOV lanes, including the provision of traffic monitoring equipment to detect incidents and facilitate their remediation.

Interim Use

Construction

No information on this topic was found in an online manual or policy document.

Special Events

No information on this topic was found in an online manual or policy document.

Emergency/Natural Disaster Use

No information on this topic was found in an online manual or policy document.

Performance Monitoring and Evaluation

Performance Measures

LA Metro conducted a study to develop a comprehensive monitoring and evaluation program for the Los Angeles County HOV system to help answer some of the many questions relating to managed lane performance. The resulting evaluation plan (*198*) provides a comprehensive approach for evaluating the performance of the freeway HOV system in Los Angeles County. The plan serves as a guide for assessing existing and future HOV facilities. It presents the objectives of the Los Angeles freeway HOV system, the measures of effectiveness associated with these objectives, and guidance on data collection, data management, monitoring, and evaluation procedures.

CDOT (*193*) has quarterly performance reports on various aspects of its I-25 Express Lanes. Performance measures include volume and lane usage, bus travel times, revenues, incidents, enforcement, operational issues, and hybrid vehicle utilization.

VTA (*221*) has a multimodal performance measures element to define specific performance measures that evaluate how well the transportation system serves the traveling public. VTA collects data on the performance measures annually as part of its monitoring process; it uses the data to evaluate and set priorities for the county's multimodal transportation system. Under the state's Congestion Management Program (CMP) statutes, the performance measures guide the development of other CMP elements.

Nevada DOT's *HOV/Managed Lanes and Ramp Metering Policy Manual* (*203*) describes overutilization and underutilization as follows:

- A project will be considered overutilized when its volume experiences degradation below speeds of 30 mph (LOS C) 25 percent of the time during peak hours. NDOT will be the primary agency to address various management measures to restore acceptable level of service in partnership with affected local agencies. Options to address overutilization include raising occupancy requirements for the affected hours,

pricing lower-occupancy vehicles, altering access, or taking other measures to manage flow.

- A project will be considered underutilized if demand for a single directional lane does not exceed 800 vph in the peak hour after five years of operation and if adjacent traffic LOS during this same comparable period is below LOS D. Both conditions must exist at least 75 percent of the time during defined peak periods. Off-peak hours (i.e., midday and nighttime hours when the freeway is not experiencing peak-period congestion) are not considered subject to this condition unless congestion is regularly experienced in this period. Options to address underutilization include adding other user groups (trucks), opening to single-occupant priced vehicles (HOT lane operation), increasing access, increasing transit and rideshare promotion, and expanding the project limits to generate greater demand.

NDOT also says that defining and applying performance measures will be based on addressing the regional and project-specific goals and objectives adopted when the project was conceived and implemented. Example objectives and measures of effectiveness are shown in Table 91.

Data Needs

NDOT (*203*) says that most of the data noted for the measures of effectiveness are typically available from local modeling, traffic data, and other members of the team involved in the implementation and operation. Data should be collected in advance of the project opening to allow for a before-and after evaluation comparison. Obtaining data for two to three years along the general-purpose lanes (preferably prior to any construction activities) will allow for trend analysis. The following items are basic information needed for such studies:

- Vehicle counts for general-purpose and HOV/managed lanes.
- Occupancy counts.
- Travel time and speed information for general-purpose and HOV/managed lanes.
- Safety and crash data by facility type (if possible).
- Violation and enforcement data.
- Survey information to gauge attitudes from users and nonusers.

Monitoring and Evaluation

No information on this topic was found in an online manual or policy document.

Reporting

In Nevada (*203*), each time an HOV/managed lane project is implemented in a new corridor, operational performance will be documented through a one-month, six-month, and first-year performance report. After initial opening, this reporting process can be facilitated through annual reporting for the respective region. An annual inventory of projects will be kept and updated for performance data. A cycle for reporting will be established that may be regional or statewide.

VTA (*220*) issues semi-annual reports on all facilities within its highway program. The report includes summaries of each project in conceptual study, environmental/preliminary engineering, final design, or construction, as well as a status update on existing facilities.

Table 91. Sample objectives and corresponding measures for HOV facilities.

Objective	Measures of Effectiveness
Improve capability of moving more people	• Number and percent increase in person movement • Actual and percent increase in average vehicle occupancy rate • Number and percent increase in carpools and vanpools • Number and percent increase in bus riders
Provide travel time savings and a more reliable trip	• Comparison of the peak-period, peak-direction travel time in the HOV to adjacent general-purpose lanes • Increase in travel time reliability for vehicles using HOV lanes
Increase per-lane vehicle volume of the freeway	• Change in the peak-hour per-lane vehicle volume on the total freeway
Increase safety and performance of transit service on the corridor	• Improvements in vehicle productivity (operating cost per vehicle-mile, operating cost per passenger, operating cost per passenger-mile) • Improved bus schedule adherence on portion of route using the HOV lane (on-time performance) • Crash rates for affected bus trips (before and after)
Not adversely impact safety and operation of other freeway traffic	• Number and severity of crashes for the HOV and general-purpose lanes • Crash rate per million person miles of travel • Crash rate per million vehicle miles of travel
Enhance impacts on air quality and energy consumption (versus no-build condition)	• Number and reduction in emissions (amount per passenger) • Number and reduction in total fuel consumption (amount per passenger) • Number and reduction in growth of vehicle miles of travel and vehicle hours of delay • Be a cost-effective improvement • Benefit-cost ratio • Benefit per traveler compared to other facility investments
Generate revenue to cover pricing cost or fund operations and capital invested	• Gross revenue generated by tolling the managed lane • Net revenue generated excluding operation and administration
Have public support	• Support for the HOV or managed lane facility among users, nonusers, general public and policy makers • Violation rates (percent of vehicles not meeting occupancy requirements)

Source: (*203*).

Evaluation Tools

No information on this topic was found in an online manual or policy document.

Maintenance

Preventive Maintenance/Scheduled Closures

No information on this topic was found in an online manual or policy document.

Response and Repair Requirements

No information on this topic was found in an online manual or policy document.

System Availability

No information on this topic was found in an online manual or policy document.

Winter

No information on this topic was found in an online manual or policy document.

Tolling and ITS Equipment

SANDAG has a policy document (*217*) describing the entirety of its concept of operations for electronic toll collection on the I-15 Managed Lanes, including topics such as system parameters, variable toll rate structure, signs and vehicle identification systems, and staged system implementation.

Enforcement Areas

Other than the information summarized previously, no information on this topic was found in an online manual or policy document.

Emergency Pullouts

Other than the information summarized previously, no information on this topic was found in an online manual or policy document.

Pylons and Other Separation Hardware

Other than the information summarized previously, no information on this topic was found in an online manual or policy document.

APPENDIX C

STATE OF PRACTICE

OVERVIEW

As part of the effort to document national guidance for the development and implementation of managed lane systems, the research team engaged managed lane practitioners and researchers to explore priority gaps in understanding and guidance for the development of new managed lanes. This appendix summarizes findings from two processes conducted for the research project.

The first process involved one-on-one stakeholder interviews conducted January 27, 2014, to February 14, 2014. A total of 18 state departments of transportation and regional operating agencies were contacted to conduct one-on-one interviews by phone, with 11 successfully completed. The second process consisted of a group survey conducted with the TRB Managed Lanes Committee (AHB35) on January 15, 2014, concurrent with the TRB Annual Meeting in Washington, DC.

For both activities, data collection was led by researchers with Parsons Brinckerhoff, under contract to the Texas A&M Transportation Institute.

METHODOLOGY

Stakeholder Interviews

The stakeholder interview process began with an email message sent to identified staff members of public agencies that operate or are in development of managed lane systems. The email text was approved by the Texas A&M University Institutional Review Board on January 6, 2014. The email, addressed individually to the staff identified by Parsons Brinckerhoff researchers, explained the purpose of NCHRP 15-49 and how data collected in the interviews would be used to guide research topics for inclusion in the final guidelines. It went on to inform the recipients that they would be contacted to schedule an interview and requested their participation.

The purpose of the interviews was to explore stakeholders' guidance for specific topical areas of managed lane planning, development, implementation, and operations and identify areas of new research and documentation from which operators/agencies believe they could benefit. Three primary questions were posed of interviewees:

1. In developing (your) managed lanes, for which topics and issues did you seek guidance but found the available guidance to be lacking sufficiency to address those issues?
2. Looking ahead to the next 5–10 years, what emerging trends do you see as requiring advance consideration and guidance in this research?

3. What lessons learned and/or best practices has your organization uncovered in the development of managed lanes, from which other practitioners could benefit?

Each stakeholder interview was conducted by phone, for a variable period between 30 minutes and one hour. In accordance with the protocol, no recordings were made of the calls; all input was documented immediately by the researchers.

Managed Lanes Committee Survey

The annual meeting of the Transportation Research Board Standing Committee on Managed Lanes (AHB35) was held at the Marriott Wardman Park Hotel in Washington, DC, on January 15, 2014, from 10:15 a.m.–noon EST. During the course of this meeting, Parsons Brinckerhoff, with support from Texas A&M Transportation Institute researchers, conducted a survey of issues with the assembled friends and members of AHB35. The researchers provided an overview of the NCHRP 15-49 research effort at the meeting, and participants were asked to provide suggested areas of focus for the research effort, keeping the following two questions in mind:

- What do you know now that you wish you had known while developing your managed lane project(s)?
- What information would be helpful to you in developing managed lane projects that is not readily available in other sources?

In accordance with the protocol, no recordings were made of the discussion.

SYNTHESIS OF FINDINGS

Nine key research topics emerged through the course of both the stakeholder interviews and the committee discussion. These topics are explored below in greater depth.

Pricing Approach and Messaging to Travelers

Managed lane practitioners identified a key shortcoming in guidance on the use of pricing in complex managed lane systems. As described, existing implementations have largely pertained to discrete segments where the price to travel on the facility was easily understood and conveyed to travelers. For example, initial implementations such as the 91 Express Lanes in Orange County and the I-15 Express Lanes in San Diego used a single price for entry, with no intermediate ingress or egress. Subsequent projects, such as SR 167 in Seattle and I-394 in Minneapolis, implemented intermediate access points, but the origin/destination profile of the corridors still involved a cumulative flow perspective, with minimal egress (inbound) or ingress (outbound) in the middle of the facilities. Consequently, the pricing approach resembled that of the single-entry/exit facilities, and segmental pricing continued to work.

More contemporary managed lanes in development, however, are more complex than the operational facilities. In particular, longer managed lanes with intermediate generators and attractors of traffic are under construction, complicating the use of segmental pricing in a logical manner. Additionally, interconnected managed lane facilities on separate freeway corridors complicate the ability to price-manage bottlenecks, merge points, and diverge points

across the intersecting facilities. Practitioners are seeking new guidance on how to properly price these complex facilities, how to provide timely and useful information to motorists, and how to standardize signage and other guidance across facilities, particularly with multiple jurisdictions. Ultimately, how can the implementer evaluate how to help customers understand and appreciate the costs involved with using the facility?

Key questions that must be resolved in this research include:

- How should implementers price long facilities with intermediate ingress/egress to mid-corridor attractors and generators? For example, what are the trade-offs between per-mile pricing, per-interchange pricing, major-destination pricing, and end-of-line pricing?
- How should implementers convey pricing information on roadway signage, particularly on longer facilities or in interconnected networks of managed lanes? Are there thresholds for price lock-in with the signage, or is there an allowance for changes in pricing to the motorist as a result of downstream changes in traffic patterns?
- How will motorists respond to the pricing of multiple segments in one trip? Will motorists weave around certain toll segments, or will they tend to remain within the managed lanes across toll segments? Is there a value in determining different pricing thresholds to encourage contiguous trips within the managed lanes? How should the price for these trips be presented to motorists in order to increase understanding, improve effectiveness in making demand-related decisions, and minimize the requirement for cumulative math for determining trip price?
- How does the pricing approach change if the implementer is looking to generate sufficient revenue to meet minimum bond obligations?
- Published schedules (time-of-day pricing) may be more favorable to resolving public understanding for longer trips and interconnected managed lanes due to the ability to predetermine the price before initiation of the trip; however, this eliminates some ability to actively manage the facilities for traffic operations. What are the trade-offs from a variety of perspectives between these two approaches? How should implementers value different criteria based on the context for implementation? What hybrid systems may be available?
- What may be allowable on roadway signage for facility branding, multiple payment classes, and vehicle eligibility? Some practitioners are implementing variations on toll rates based on axles, occupancy, pay-by-mail, and emissions. How can these different rates best be communicated?
- What is the optimal signage in advance of ingress locations? Some locations only use one advance pricing sign, whereas others have up to three signs before ingress. What is the proper location, number, and deployment of toll rate signage?

Access Considerations

The consideration of access into and out of a managed lane facility was cited by many stakeholders. In particular, agencies implementing managed lanes have determined there is no set guidance on how to determine a separation and access scheme; where to locate ingress and egress points relative to origins, destinations, attractors, and generators; and how to best

determine the utilization and operational impact of the access points. Multiple subsets of this issue are described below.

Limited vs. Continuous Access

Lane separation strategies continue to be discussed and debated by practitioners. Initial managed lanes opened with some form of positive separation (i.e., channelizers or barriers), but subsequent facilities opened with painted buffers and no separation. Practitioners have evaluated the lane separation primarily on cost and geometric constraints; however, comments received in this process indicate that the presumption toward reduced costs may come at the expense of higher violations and lost revenue due to perceived unfavorable reactions from customers for travel time reliability. As a result, practitioners are seeking guidance on the impacts of weaving, toll zone avoidance, lost revenue, and accounting issues with different access and separation types. Furthermore, they seek design guidance on the differences in separation and access treatments for one- and two-lane managed lane facilities as well as necessary toll zone placement and frequency with different designs. This guidance should take the form of articulating where and how to design access in relationship to overall program goals and objectives. For example, if the intent is to reduce costs as much as possible, then what does that objective mean in terms of selecting the type of access? Although continuous-access design may reduce pavement and right-of-way costs, it also may require higher densities of readers and signage (including the power, fiber, and other components necessary to make this happen) than in limited-access design. As a result, is there the opportunity to detail the relative costs, benefits, and trade-offs between the various access and separation schema in order to offer more definitive guidance in design?

Additionally, practitioners expressed an interest in understanding the appropriate scale of operations analysis in order to determine the preferred separation and access schema. For example, are microsimulation tools necessary and cost effective, or are alternative mechanisms appropriate to address these issues? Furthermore, are the evaluation tools effective in yielding valid results when implemented in the field?

Ingress/Egress Locations

The issue of price signage, as described above, goes hand in hand with the consideration of access. In a limited-access setting, does the pricing influence the use or nonuse of access at designated locations? As one practitioner noted, the industry tends to look at access locations from an operational perspective independent of pricing; however, this individual noted that such an approach may not be appropriate due to the use of pricing as a meter unto itself. Consequently, practitioners are seeking guidance on appropriate criteria on how and where to place access points, and how to evaluate these locations over time. For example, what happens to access location if downstream general-purpose lane congestion increases over time to the point where queuing begins upstream of the ingress point? Published research, as noted in the literature review, indicates that such a condition lends itself to buffer-crossing violations as motorists illegally enter the managed lane upstream of the ingress concurrent with the location of upstream queuing. As a result, should the points of ingress and egress change over time to respond to general-purpose lane queuing, and if so, what are the impacts

to safety, pricing system performance, and overall corridor operations? How can ingress and egress points be separated to better reduce weaving and increase safety?

Direct-Access Ramps

In interconnected facilities, the use of direct-access ramps would appear to be preferred, but they also come at great capital cost. Agencies are seeking resources to determine the necessity for direct-access ramps relative to these costs. Desired guidance includes potential minimum and maximum movement volumes between the two managed lane facilities that would lend themselves either to preferred or mandatory direct-access ramp considerations. Additionally, practitioners seek guidance on phasing—can the direct-access ramp be provided in subsequent phases? Similar metrics would also be desired for considering intermediate access to arterials, bus park-and-rides, and other points of access between the managed lane facility and intersecting transportation infrastructure.

Interconnected Facilities

Initial managed lane facilities involved the conversion of existing, discrete HOV lanes that were underutilized, and as a contributing factor, often disconnected from other HOV lanes in the region. However, in the past five years, many regions (including those interviewed in this process) are actively developing networks of managed lanes that involve interconnected facilities from one corridor to another. Practitioners who are exploring these concepts indicated a concern regarding design, customer interaction, business rules, and challenges with cost and revenue sharing at the points of intersection.

When two facilities come together, a change in the business rules from one to the next could initially cause confusion on the part of customers and, over time, create overall traffic management issues at the point of policy divergence. Furthermore, independent of business rules, two facilities that intersect must have correct balancing of infrastructure relative to their market demand. For example, imagine a two-lane managed lane coming to a diverge point, falling into two one-lane facilities. In a perfect world, 50 percent of the two-lane facility traffic stream will be destined to one corridor, and the other 50 percent to the other corridor. This would allow for the maximum loading volume within the upstream corridor. However, such a distribution is unlikely to be the case. As a result, the system operator is faced with two options, each of which must be evaluated in the context of the individual corridors and operating agencies: increase capacity in the dominant direction, or use differential pricing to encourage demand balance through market forces.

The development of managed lane networks poses a challenge different from that of linear corridors. Practitioners expressed a desire to understand how costs and revenues can be appropriately shared between corridors, especially with different owners and/or operators. For example, revenues are typically distributed by where the tolls are collected, not where the value of travel time savings is found or where the operational cost is incurred, which could be a problem as networks are built out around the United States. Furthermore, what are the appropriate operational performance targets for networked facilities? Practitioners expressed

a concern that degradation in one segment will negatively affect another segment, so what guidance can be offered when the operators between the two segments are different?

Designing for Reduced Standards

The 2004 AASHTO HOV guidelines (*3*) include a trade-off analysis on various design options for reducing width from standards. In the time since publication, additional operational strategies for managed lanes have emerged, including the use of dynamic shoulder lanes, active lane control signals coupled with variable speed limits, and reduced lane widths in order to accommodate new managed lane facilities. Practitioners expressed a desire for more definitive guidance regarding designing managed lanes in constrained conditions. For example, what is the appropriate order of trade-offs between buffer widths (or exclusion thereof), shoulders, and travel lanes? What should be cut first, what are the trade-offs as identified by practice, and what should serve as hard lines that should not be changed? One practitioner cited the reduction of lane widths, when used to accommodate an additional lane of travel, as having contributed to reduced weaving that yielded fewer crashes on the corridor.

For the use of inside shoulders for managed lanes, initial operations involved part-time operation of the shoulder lanes as managed lanes. However, practitioners desire an understanding if part-time or permanent conversion is a preferred solution based on safety, enforcement, operations, and maintenance costs. Furthermore, this guidance provides them with an opportunity to evaluate the effectiveness of shoulder lanes operated as managed lanes.

Multiple practitioners indicated that adequate space for enforcement is often eliminated in constrained conditions. Guidance is desired on means of providing safe and visible enforcement at the front end of project development so that adequate enforcement can be provided even as other design trade-offs are considered. Although not a design challenge, perhaps the use and availability of new technologies for enforcement may allow for further reduced design standards for field-based enforcement. In this case, adequate guidance should be offered for providing flexibility of enforcement mechanisms, be they video enforcement, automated occupancy detection, or other mechanisms.

Operational Differences Between One- and Two-Lane Facilities

Managed lanes have opened in both single- and dual-lane configurations. Since opening, agencies have observed a general trend toward higher revenue generation and operational performance with dual lanes, but lower costs of deployment on single-lane systems. As such, practitioners developing managed lanes are trying to assess the trade-offs between these two broad options.

From a physical design perspective, does the selection of dual lanes yield specific requirements for separation and access? If the facility is buffer-separated, can buffer breaks be used for access, or must transition weave lanes be implemented? What are the best practices and appropriate trade-offs relative to design and operations when implementing a dual-lane facility?

In terms of addressing broader issues of revenue and return on investment, practitioners are also seeking guidance on how to evaluate the operational impact of a dual-lane facility beyond the additional capacity. What are the differences in revenue generation? Are there substantial differences in the toll collection as a result? How does the dual-lane facility impact general-purpose lane and managed lane operations as compared to single-lane facilities? For example, what are the impacts on crashes, travel time reliability, and weaving? Could such a facility lend itself more toward the allowance of multi-axle trucks to use the facility? Finally, does the number of lanes indicate the necessity of direct-access ramps?

Toll System Design

Toll systems have become a standard component of all priced managed lanes, yet there are no documented standards for the design and cost estimation of the toll components on managed lanes. Toll system design includes the selection of standardized hardware (such as cameras, antennas, and computer servers) and customized hardware and software components to serve toll collection, including specific transponder readers and other lane-based systems, in addition to back-office accounting of toll transaction and collection activities. The deployment of the specific toll system design is influenced by many factors, such as the availability of the physical facility, staffing constraints, development of the system, legislation, funding, marketing, and coordination with other stakeholders.

Practitioners stated that the custom aspects of toll system design have left agencies at a significant disadvantage as it relates to specifying requirements for tolling in cost estimation, design, construction, and ongoing operations. One practitioner stated as a lesson learned that the tolling industry is its own industry, and that the agency did not appreciate the complexity and proprietary nature of the integrated systems until it was involved in the implementation. In addition to developing standards on components, practitioners stated a desire for guidance regarding the placement of toll zones, specifically on how to identify those locations, and what specific limitations or opportunities should be sought for optimal conditions. Furthermore, practitioners would like to reduce their reliance on vendors to describe the capabilities of tolling in the field, as well as receive guidance on how to plan for a change in vendors over the life of a facility.

Additional issues pertained to specific toll collection issues. These issues included:

- How does the facility operator assemble trips across multiple toll zones into one toll transaction for invoicing purposes?
- What guidance exists toward developing a testing plan for calibrating a pricing system before going live?
- How are toll accounts maintained over time by DOTs and toll agencies? Would alternative payment systems (e.g., banks/credit card companies, national toll payment processors, etc.) change the requirement for toll operators to maintain actual accounts?
- To what extent should low-cost transponders (such as ISO 18000 6C transponders) enable broader distribution? What are the trade-offs between providing a tag for everyone opposed to conducting pay-by-mail and other video-based solutions?

- Should toll readers be suspended over general-purpose lane traffic in order to better monitor traffic conditions and responsiveness of managed lane toll algorithms?
- How should toll operators plan for national interoperability requirements and emerging connected vehicle technologies? Do these systems affect frequency of signage, transponder technology selection, and even design of the facilities?
- How could toll system standards enable better enforcement practices, including spacing, technology, and policy, as they pertain to occupancy?

Vehicle Class Preferences and Enforcement

Managed lane implementation in the United States began primarily as bus and HOV lanes. As such, even as facilities were converted into priced managed lanes, preferences for carpools and buses were maintained—almost exclusively in the form of toll-free use of the priced managed lanes. However, as more contemporary priced managed lanes are being constructed independent of existing HOV lanes, or in some cases, as an expansion on HOV lane corridors, practitioners are questioning the appropriate role of vehicle eligibility and preference in these facilities.

For facilities already functioning with HOV and other vehicle class preferences, practitioners are concerned with identifying thresholds where the lanes become degraded. Many priced managed lanes in Los Angeles, San Jose, and Houston already operate in HOV-only mode during certain conditions, where systems lack available capacity to sell to toll customers. Practitioners desire guidance on how to justify a change in vehicle class preference policies, and whether a preferred solution is to increase the requirements or eliminate exclusions and preferences altogether. In particular, one participant stated that current carpool formation models are insufficient to answer the effect of toll-free travel on carpool formation, and that this information is necessary to continue to justify HOV preferences in congested facilities. If a change is warranted, practitioners seek additional guidance on how these changes should be pursued with policy and public outreach.

For many practitioners, the issue of vehicle class preferences on managed lanes affects not only the consumption of available capacity in the managed lanes but also the ability to adequately enforce the lanes. As mentioned above, new technologies should be identified, evaluated, and monitored for occupancy validation. The use of switchable transponders should also be evaluated. Together, practitioners are seeking guidance on the effectiveness of these elements in resolving enforcement-related issues.

For facilities that are new construction without preexisting HOV lanes, practitioners are trying to determine the rationale for toll exemptions. Many stated that there is a need for guidance regarding requirements (or lack thereof) for toll exemptions, a trade-off analysis for offering exemptions, and an assessment of the benefits of offering exemptions against the operation cost of providing such.

Inter-Jurisdictional Issues

Each corridor and each region is different from one another, and this informs decisions regarding the design, operations, and business rules for their managed lanes. As guidance is developed, it needs to reflect context in the design and implementation. Some practitioners desired definitive guidance, whereas others desired best practices in order to learn from others and adapt to the local context.

Different toll operators have different objectives for design. What happens when these different operating rules come together as a system? How should preferences in one jurisdiction interact with others when there is no one global interaction standard for accounts, violations, fines, rules, and other factors? What happens when one jurisdiction has a different preference than another, and the two facilities intersect?

The Business Case for Managed Lanes

When discussing the implementation context for managed lanes, many practitioners cited the lack of business analysis in the planning process. The systems of managed lanes are inherently a business decision, given the overall requirements for customer interaction, marketing, customer service, branding, messaging, invoicing, and other affiliated components. How to properly execute these functions and how to do so in regards to the customer experience on the freeway system are business decisions, not traffic management decisions. Practitioners stated, though, that guidance is greatly lacking on how to run their transportation organizations as a business that is well suited to managed lanes.

Design decisions can also be affected by the business case for managed lanes. For example, separation requirements or construction of direct-access ramps may be necessary to better enable private-sector financing for the construction of the facility. Practitioners seek guidance on how to analyze regional business decisions for corridors when the environmental process is intended to examine discrete improvements for the corridor's needs exclusively. In this case, guidance is desired for how to have managed lane concepts and design articulated at the front end of environmental documentation, including what is viable in the long run.

Finally, how to allocate costs and revenue is a key business decision. In particular, the cost to operate a managed lane facility is a moving target. Infrastructure that preexists may be repurposed to managed lanes. For example, closed-circuit television (CCTV) cameras that were 100 percent devoted to general-purpose traffic are now partially shared with managed lane traffic monitoring. Do the maintenance expenditures now need to be shared between the two facilities for these CCTV cameras? If so, it will require better accounting in order to provide an appropriate offset. Appropriate applications of other traffic operation options, such as ramp meters, must also be considered.

APPENDIX D

LIST OF INTERVIEW QUESTIONS: ASSESSMENT OF THE ROADWAY DESIGN DECISIONS MADE BY DEVELOPERS OF PRICED MANAGED LANE SYSTEMS

OVERVIEW

As part of the effort to document recent design experience and incorporate it into the latest managed lane guidance, the research team engaged managed lane practitioners and researchers to gain an understanding of how design decisions are being made on managed lane projects by agency sponsors. This appendix describes the interview questions used to obtain that information for use in identifying common practices and developing recommendations for guidance.

An expansive list of questions forming a discussion script was developed for practitioner meetings. The basis for questions was to capture both the process that agencies went through in responding to their specific project goals and objectives and in documenting the rationale behind design selection including influencing factors. Major aspects of design from tolling systems to enforcement and incident management were included.

Discussion topics addressing design are developed in the following categories. Not all categories apply to the four design paradigms (multilane new construction, single-lane new construction, multilane conversion, single-lane conversion). Conversions need to focus more on legacy issues that influenced the design outcomes, such as the type of users that were previously on the HOV lanes, type of separation and access, and hours of operation. New construction needs to dwell more on the design setting and prevailing practices that are preferred by the sponsoring agencies. This script is intended to serve as a resource for all discussions with practitioners.

AGENCY CONTEXT AND BACKGROUND

- What management strategy and anticipated benefits was the design intended to address?
- Were any measures of effectiveness employed at the outset of design? If so, what were they?
- Were there any unique criteria considered that differed from this being a standard highway project design? If there was any unique design aspects, do you think the final design adequately addressed these?
- How did the concept for this project get started? Who moved it forward?
- What challenges were faced in moving it forward? What opportunities?
- Were there any influencing factors that caused the project to move forward (e.g., funding, other improvements planned, legislation or local initiatives)?
- Who are the agencies and agency departments directly involved in implementing this project?

- If multiple agencies are involved, what are their roles?
- Who was included for design input? Who was not and why? Specifically, were enforcement, maintenance or tolling, or operating units involved in providing input to project design? If later on, when in the process were they involved?
- Have agency roles changed since the project was implemented, or began operation?
- Within the participating agencies, what parties had the greatest influence and role in design and development decisions? Why?
- If the interview involves a P3 partner or local (non-state DOT) agency partner, try to obtain a better understanding of how they envision their role relative to the DOT, and how they relate to the design decision process.

Design Setting

- Can you briefly describe the design setting for the project? (age of road and bridges, # of lanes, variances in ROW and designs, who uses it, regionally comparative level of congestion).
- What were the most significant design constraints and opportunities you encountered? (Try to develop a list and separate design constraints from opportunities, exploring how both played a role in the project design.)
- What were optional solutions to each constraint on the list?
- What was the recommended solution or strategy for each constraint?
- Was solution implemented? Why or why not?
- Are any of these solutions likely to be confronted or implemented in the same way on your next ML project?

Design Attributes

Each common and unique aspect of the project design needs to be explored, with a sensitivity toward transferability of experiences to other similar projects. Where possible, examine commonalities or unique ways the practitioner addressed the design decision.

Overall Operation and Design

- How did the planned management strategy and desired benefits (MOEs) influence project design decisions? For example, did the type of vehicle or operating rules determine what design would be applied? And vice versa, what design issues required changes to desired operation policies?
- Did funding, procurement, construction, maintenance and operation roles influence design decisions, and if a D-B or P3, how much latitude was given to designers?
- What were overall design issues this project had to live by? Examples might include staying within ROW, not encroaching on # and width of mainlanes, preserving right-side shoulder, etc.
- How were the project limits established? What role did design play into setting these limits?
- Is this project being staged with multiple openings? What factors influenced interim termini?

Cross-Section

- What was your universe of potential project cross-sections? What factors were considered in narrowing down these to what you selected?
- What did you initially recommend? What was ultimately adopted? If different, what factors led to the adoption?
- What degree of variance is in your overall design section (combination of left shoulder, lane width(s), buffer or separation stripe or barrier)? What factors influence this variance?
- Where the desired design does not fit, what was the first design attribute to reduce and why? Second? Third? Would you use this same hierarchy for arriving at what would fit best the next time?
- What were existing impediments that could not be altered (i.e., bridge columns, sign structures, etc.)? How did you address these?
- What drainage issues were confronted and how were these addressed? At curves and superelevations?
- What sight distance issues were faced and how were these resolved?

Separation

Separation is defined as the space or treatment between the managed lane and GP lanes.

- Assuming your project is not part time and reverts to GP use during certain hours of the day, what type of separation did you adopt between the ML and GP lanes? Why? What other projects did you investigate or review in making this design decision? What safety issues were raised? What options did you first look at, and what did you adopt? What has been the outcome? Would you choose a different approach now?

Shoulders

Shoulders are defined as the ML space usually located outside the travel lanes and median barrier and right-side barrier if physically separated.

- Are full or partial breakdown shoulders provided on your project? If yes, how much of the total project distance? What are the widths of shoulders available for vehicle breakdowns next to the managed lane(s)?
- Are these shoulders used for ML enforcement monitoring or apprehension?
- How did you reach a design determination over the inclusion/exclusion of designated shoulders? What trade-offs were involved?

Access

- If you apply at-grade access with the adjacent GP lanes, what frequency did you establish these? Why? What is the design applied to enter or exit (separate ingress/egress or shared, use of weave lane or weave zone)? What factors influenced your selection of a particular at-grade design? What operational studies did you consider or apply to determine weaving impacts to both traffic streams?

- If you apply direct access, what type is applied (e.g., drop ramp, flyover, tee)? Why? What is the design speed of each? What is the anticipated level of traffic volume? Did these require new ROW or other impacts?
- Begin project: How does your project begin? Are there multiple ways to enter, and if so, how were these established?
- Termini: How are downstream termini conditions handled (i.e., continuation of a GP lane or lane drop from the left)? What operational conditions influenced this design decision?

Signing, Markings, and Other Traffic Control Devices

- What were the most critical signing needs unique to this project?
- If a converted project, was prior HOV signing augmented or were most all signs replaced and updated?
- What are signing practices on your project? Overhead, side mount on barrier, both? For what types of signs? What typical sequence of large and small signs are used?
- What signing issues were the most challenging? Why?
- If project is not concrete barrier-separated: What options for pavement markings were considered and what was the implemented pavement separation marking?
- What have you observed as being the pavement marking treatments providing the greatest benefit to effective operations?
- What changes in signing and marking were undertaken after opening and why? Are any changes planned for the future?
- How many downstream destinations are noted on toll pricing signs?
- What strategy for prioritizing messages was used?
- Was the MUTCD followed? If so, what issues were encountered in trying to apply the MUTCD guidance?
- Once a decision was reached on message prioritization, who took the lead in determining what was reasonable to include within the highway environment versus what/which message had to be dropped due to message overloading, sign crowding, structure capabilities, etc.?

Site Enforcement Provisions

- What design provisions were included to address enforcement monitoring and apprehension? (Try to get a specific list and identify what design treatments were used for each if they are unique to the managed lane design.) What were widths, tapers, other attributes?
- How did you arrive at design decisions supporting enforcement needs? When in the design process, were enforcement representatives brought in to provide input?
- What enforcement design provisions were considered versus applied in the field? Why were some ideas ruled out?
- Are enforcement officers using the designs as intended? If not, what have been their reasons?
- Are any design changes planned in response to enforcement activities?

Tolling Infrastructure

- What was the primary purpose of your tolling system—to better manage traffic on the lanes or generate revenue to offset costs?
- What factors were considered in the location of tolling gantries?
- Who is charged with tolling operations (if not your agency)? What role did they have in providing input to tolling substructure and substructure?
- How are tolling systems mounted? How did you arrive at these decisions?
- How are maintenance needs provided for in the selected design (at the reader and camera locations)?
- Are tolling systems free standing or shared on other structures? If hung from other structures, what evaluation did you undertake to determine how to design these?
- Looking forward, would your agency change anything regarding tolling system design?

Maintenance

Any specific maintenance considerations made in designs for:

- Tolling infrastructure.
- Emergency management/incidents.
- Snow or winter weather events.
- Drainage.
- Transit design provisions (i.e., may be related to locating at-grade access points, off-line or on-line bus stops and stations).

Follow Up

If project is operational, follow up with these questions:

- Has there been any design changes to the project since opening? If so, what changes and why?
- Have there been any operation or policy changes that have required changing the design? If so, what were they?
- Are any design changes pending? If so, what are they?
- Are there any standards of design practice that your agency has adopted or would change based on this project's design experience? If so, what are they?

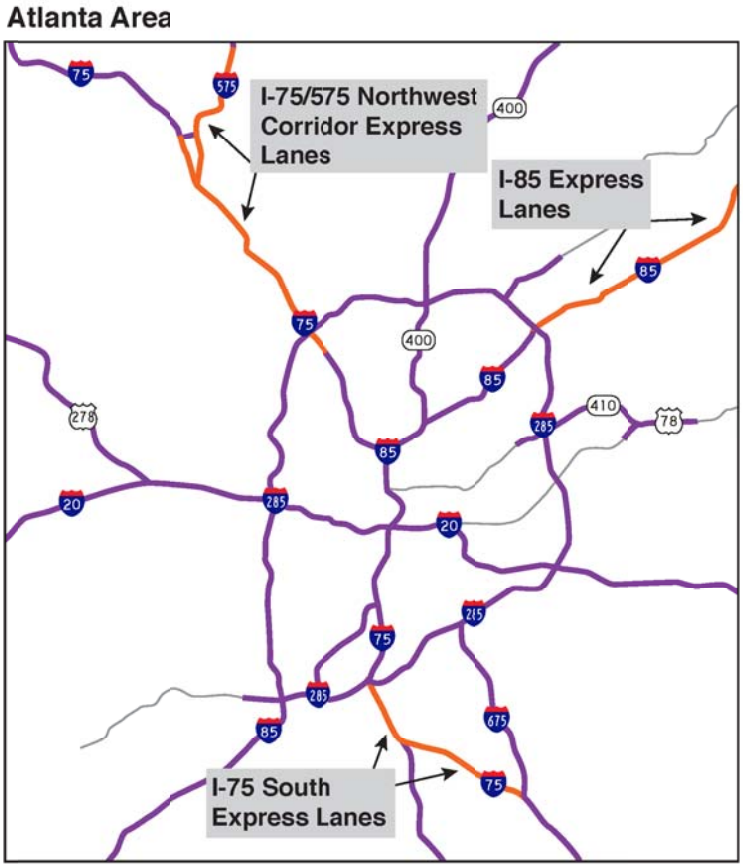
APPENDIX E

CASE STUDY REGIONS

The following case studies offer insights into the local context for decision-making that led to adopted designs and local practices. Five initial case study regions were selected: Atlanta, Bay Area, Dallas–Ft. Worth, Los Angeles, and Seattle. After discussions were conducted with respective regions, a sixth location was added to capture decision-making that includes transit facilities since no other location incorporated transit facility design within its toll managed lane development. The case studies are presented in alphabetic order.

ATLANTA REGION

Three express lane projects are in operation or under construction in the greater Atlanta area. They are shown in Figure 48 and described in the following sections. I-85 is considered a conversion project in a separate case study from the other two projects, which are considered new construction.



Source: TTI

Figure 48. Express lane projects in greater Atlanta area.

Background

The greater Atlanta region began planning for HOV lanes during a period of freeway modernization and widening back in the 1980s. As Atlanta's original freeway system inside I-285 Beltway was widened, environmental documents required HOV lanes as a mitigation strategy. While these lanes were originally opened and used by general-purpose traffic for the first few years, the HOV restriction was eventually instituted in time for the 1996 Olympics and retained in accord with environmental agreements after this date. Original lane design was concurrent and contiguous without any buffer separation. Incorporating HOV lane restrictions involved converting median shoulders and reducing some lane widths in order to create an added lane. Taking the innermost general-purpose lane and converting it would have created too much traffic impact and public backlash. The same number of GP lanes was retained, and the resulting HOV lanes exhibited a constrained design. This approach was applied to I-75 and I-85 inside the I-285 Beltway in central Atlanta including a portion that became HOT lanes more recently. Atlanta's HOV lanes were operated 24/7 for 2+ occupant carpools, transit, and motorcycles. However, more than a decade later, general agency consensus was that the HOV lanes were failing due to high demand and inadequate enforcement.

Obtaining a federal urban partnership agreement offered Atlanta a chance to test pricing on the region's HOV lanes. Initially, the local intent was to consider adding pricing to all of the region's HOV system, and after preliminary review, a grant application was prepared for I-85 as the region's first high-occupancy toll lane project. Goals for this project included improving travel time reliability, maximizing existing roadway assets in providing options to commuters, and improving transit service in the corridor.

This portion of the I-85 HOV lanes was subsequently studied to incorporate electronic tolling in March 2008. The project was awarded a federal grant in November 2008, and it was subsequently converted to an HOT lane, which opened in summer 2011. Operation policy changes made at the time of conversion allowed free use by registered 3+ occupant carpools and tolled use by all other vehicles except large trucks. The HOV buffer was retained with restricted access at designated locations.

I-85 Express Lanes Project

Agency and Project Context

Georgia's first express lane project on I-85 extends 13 mi northbound and 15.5 mi southbound and starts just inside the I-285 Beltway. GDOT is the agency sponsor for the project. At the time the UPA grant was approved, Atlanta regional partners included GDOT, the Georgia Regional Transportation Authority (GRTA), and the State Road and Tollway Authority (SRTA). The majority of federal funding went to transit vehicles and park-and-ride lots in the freeway corridor. Total funding for the pilot project was $182 million, which included the express lanes, enhanced transit service, and related innovative technologies to better manage the project.

GDOT was responsible for roadway design and operations. SRTA was responsible for toll operations and collection and management of the Peach Pass account service. GRTA was responsible for transit elements. The Atlanta Regional Commission, the City of Atlanta, and Gwinnet County were involved in local coordination, such as circulation pattern improvements for the City of Atlanta. The Department of Public Safety (DPS) Motor Carrier and Compliance Division was involved with occupancy enforcement of the express lanes. Greatest influence over design decisions was exercised by GDOT for the roadway and SRTA for tolling. More information can be found online at http://www.peachpass.com/faq/.

Overall Design

The project had to meet stringent schedule requirements to be eligible for funding, so the design had to rely on using the existing HOV lanes. This approach leveraged infrastructure already in place. Signing was generally replaced, pavement markings were modified to create a greater sense of separation, gantries were installed for tolling and buffer-crossing management, enforcement technology for occupancy status was provided to police officers, and access zones were altered. Agency partnering helped meet the mandatory schedule. About 10 other priced managed lane facilities around the United States were reviewed on a scan tour before committing to a project design. Roadway changes were limited to foundations for new signs and pavement markings. Construction of improvements occurred primarily at night and on weekends. Much of the overhead tolling and enforcement equipment utilized existing sign and bridge structures where possible.

Separation Buffers and Shoulders

In keeping with the prior HOV operation, no physical separation exists along the project. Painted buffers include an indentation rumble strip under the white stripes to provide both an audible and sensory response to ingress and egress outside the designated weave zones. SRTA wanted customers to see, hear, and feel when they were entering the express lane at an inappropriate location. Options that were considered included thermal “cookies” and grooved rumble strips. The grooved strips were selected primarily due to the occasional need to plow the road during winter weather events. After the express lanes opened, northbound buffer crossing became a problem in the vicinity of the SR 316 interchange. To address this problem, approximately 1 mi of pylons will be placed in the buffer area later this year.

Design exceptions are subject to evaluation and approval when the project design cannot meet desired standards. Few new design exceptions were created with this conversion. Some prior HOV lane design exceptions were kept, including a reduction in buffer width. Typical buffers are 3 ft and involve a 12-inch white stripe, 12-inch gap, and second parallel 12-inch stripe (12-12-12), as show in Figure 49 and Figure 50. An acceptable configuration is also 8-8-8. In one isolated segment, these dimensions were reduced to 5 inches for all striping and gaps between the stripes (5-5-5).

A full inside shoulder (10 to 12 ft) is provided north of Jimmy Carter Boulevard, which represents about 75 percent of the 16-mi project distance. South of this point, the inside shoulder varies from 2 to 4 ft, which is not wide enough for emergency breakdowns.

Source: Swenson

Figure 49. Typical converted HOV lane section, before condition.

Source: Swenson

Figure 50. Typical converted HOV lane section, after condition.

Access

A total of five intermediate at-grade access zone locations are provided in each direction. Determination for placement of access zones was made by operational analysis as well as origin-destination and traffic and revenue studies. Shared ingress and egress is provided within each zone. The length of each weave zone varies from 2000 to 3500 ft northbound and 2700 to 4600 ft southbound. Factors influencing this design included using prior access locations provided for HOV operation with supplemental operation studies. A southbound access zone on the north end was added to the project after opening using temporary signing until permanent signing could be fabricated and installed.

The southbound project begins as an added lane next to the median (same as the HOV lane) and ends as an HOV lane with an access zone to weave out. Traveling northbound, the HOV lane becomes an HOT lane and continues as a general-purpose lane where the toll restriction ends.

Signing and Pavement Markings

Tolling signs for express lanes are found in the federal *Manual on Uniform Traffic Control Devices* (*42*). The local FHWA staff requested that only two lines of text be provided for downstream destinations given the limited project distance (Figure 51). Toll signing is located on overhead mounts. GDOT standards were used for other more conventional signing. A goal in prioritizing sign messages was to relay information in a simple, relevant way in order to not create information overload. GDOT and SRTA consensus was applied for signing decisions.

Double white striping as specified in the MUTCD, along with an embedded rumble strip, was used to separate the express lane from GP lanes (Figure 52).

Source: Swenson

Figure 51. Typical pricing sign.

Source: Swenson

Figure 52. Rumble strip on separation stripe.

Enforcement, Maintenance, and Incident Management

Enforcement personnel use the 10- and 12-ft shoulder segment for monitoring and apprehension activities. In the more restricted segment, they pursue violators to a safe point to apprehend. ALPR-equipped vehicles are used daily by the DPS agents under contract to provide enforcement. These specially equipped vehicles allow officers to quickly determine the account mode (i.e., SOV or HOV) to verify occupancy in the vehicle.

The express lanes can be closed on occasion per GDOT lane closure guidelines and requirements. Because of the large number of gantries involved in the toll system, loss of capability from one gantry can be absorbed by the system for a reasonable period of time until such time for lane closure can be reached.

There are times when the express lanes could be opened to all traffic and not tolled, such as in the case of a major crash in the GP lanes. GDOT has the capability to post an “Open to All” or “Lane Closed” message. However, this contingency is rarely considered because most vehicles are diverted around accidents at discrete locations and not for long distances. The express lanes may close during inclement weather. Operational policies are in place to address steps to take when this happens.

Tolling System

The project’s toll system was designed with the objective of better managing traffic, and it is considered the most sophisticated among all express lane systems that have been implemented. SRTA and GDOT coordinated on the tolling system design early in the design process. With a goal of trying to minimize capital costs in this UPA grant project, existing sign structures were retrofitted in some cases to support the tolling equipment. Where possible, co-location of toll equipment with the new sign structures was practiced. New structures were also added as necessary to support the design requirement of a tolling gantry every half mile in each direction.

A single median structure supporting two lightweight arms over each side of the roadway was designed to support the tolling equipment required. The project deployed an innovative approach for gantry-controlled access. This access management system was a first of its kind in the United States. The camera and algorithm technology could address illegal double-white-line buffer crossings within a toll segment. It required fully equipped toll gantries every half mile within a toll segment.

Lessons Learned

- **Design changes.** A new access zone was added on the north end to address overcrowding. Pylons within the buffer area in the vicinity of State Route 316 will be added to address weaving problems.
- **Sign unveiling plan.** Significant thought went into the signing plan. Once the new signs were installed, the contractor thought that it would be able to unveil signs over a significantly longer timeframe than the sponsoring agencies would have liked to avoid the possibility of driver confusion with the older HOV signs still visible. This resulted in a need to incorporate a provision into procurement documents that requires a signing unveiling plan to be developed and approved by the project owner.
- **Agency partnering.** Having strong partnering agencies and maintaining close coordination has been critical to effective design, implementation, and operation. Numerous issues arose on this first project in the Atlanta region, particularly during the first days of operation, including having the governor intervene to establish a maximum toll cap. Having close working relationships gave strength to all agencies involved.
- **Tolling gantries.** The potential to use more lightweight structures for mounting of tolling antennas may be considered depending on requirements for accuracy. SRTA mounts antennas over the GP lanes so that it can confirm which vehicle to toll and collect and compare travel time data. For a dynamically priced facility, conditions in the adjacent lanes need to be known in order to adjust the toll and operational policies for the express lanes.
- **Construction coordination.** The hand-off point between the civil engineering contractor and the toll system integrator needs to be carefully considered even if both are procured by the same agency. The standard is likely to be which contractors in the community are capable of doing which tasks in the best manner. Site turnover rules from the civil engineering contractor and toll integrator should be tightly specified.
- **Equipment testing.** The need for end-to-end on-site testing is critical, often requiring more testing time than planned. Once installed, the field-testing environment is complicated by working around traffic, most often on weekends and at night. I-85 was under a very tight time schedule that potentially risked inadequate testing.
- **Surveillance.** Sharing of cameras poses challenges in prioritizing needs. Additional cameras are needed to monitor express lane queuing and message displays since corridor priorities will be weighed toward using cameras to monitor incidents and crashes.

I-75 South and I-75/575 North (Northwest Corridor)

Two new construction projects were being developed in 2015 on opposite ends of the greater Atlanta metropolitan area (Figure 48) and are scheduled to open in the near future. Each project is located on a radial corridor extending out from the I-285 Beltway. Each has experienced a long lead time in planning and concept development. The I-75/575 project, in particular, has undergone several conceptual, financial, and delivery starts and stops. The following weblink provides the latest information on the I-75/575 project: http://www.nwcproject.com/. The projects have been influenced by changes in how Georgia transportation policies allow development of new urban highway capacity. GDOT policy states that all future urban expansion will be managed capacity, including tolled managed lanes and active traffic management on this added capacity. These projects are being pursued with this intent.

Agency and Project Context

The I-75/575 project extends 30 mi and will provide two reversible lanes from just south of I-285 to I-575, one reversible lane continuing to the north on I-75 to north of Hickory Grove Road, and one reversible lane continuing north on I-575 to south of Sixes Road. Reversible lanes in this context refer to added lanes operated either in an inbound or outbound direction behind permanently placed concrete barriers. Project limits were established during the environmental phase.

The I-75 South project extends 10 mi and provides reversible lanes as well. It addresses commuter congestion as well as special event congestion emanating from the Atlanta Motor Speedway located nearby. For this reason, the reversible lanes are not intended to operate only for weekday commuters (i.e., functioning inbound in the morning and outbound in the afternoon).

Many goals were considered for these corridors, and all regional projects were evaluated at the same time to promote mobility and reliability on managed lanes/roadways. Early multimodal planning goals included (a) improving transit service through BRT provisions, (b) providing mobility and travel reliability through high-occupancy toll lanes for HOV and general traffic, and (c) improving goods movement efficiency through truck-only toll (TOT) lanes. The widest number of added lanes studied on any route was two HOT and two TOT lanes in each direction. Cost constraints reduced the cross-section as well as push-back from the trucking industry. FTA New Starts loans could not be obtained for BRT.

Sponsoring agency roles for these projects are similar to I-85 and primarily involve GDOT and SRTA. GDOT is responsible for physical construction of the roadways, and SRTA is responsible for tolling elements. However, SRTA is the contracting agency for the I-75/575 project, while GDOT is the contracting agency for the I-75 South project. SRTA in this instance serves as "GA's Transportation Financing Arm" (*224*), so its purview includes the ability to implement and finance projects. GDOT is responsible for roadway design on both projects. Both agencies were closely involved along with FHWA in express lane design decisions on the two interstates. Numerous other agencies including Cobb County, the Atlanta

Regional Commission, DPS, and FHWA are involved in the process representing their roles in the community. Input from the enforcement, maintenance, and tolling staff was solicited early in the design process. DPS was responsible for looking at lane access in the event of an emergency situation, such as needing to reach a crash within the reversible lanes.

Project Delivery

Based on agency dialog received, GDOT used "the Texas approach" for a design-build-finance agreement, which was applied to the I-75/575 project (see Dallas–Ft. Worth case study for more discussion of this approach). The engagement of public-private partners and design-builders provided both benefits and challenges. A faster delivery and lower cost was achieved over conventional design-bid-build delivery. However, partnering requires close scrutiny on contracts and specifications. The design-build contractor is responsible for implementing the project in the most efficient and cost-effective manner possible based on specifications provided by SRTA and GDOT during the procurement. However, from the operating agencies' perspective, the most efficient design for building the project is not always the most efficient for operating it. This needs to be kept in mind as design requirements and specifications are set forth during procurement. Fortunately, good continuity between the I-75/575 and I-75 South teams occurred because both have the same subcontractors and consultants working with GDOT and SRTA. These conditions were not specified in the respective procurements. For I-75/575, the P3 approach allowed alternate design concepts to be brought forward by the contractor team and approved by GDOT.

Design and Operation

The overall design initially considered dual directional lanes (two in each direction), but after funding constraints and stakeholder preferences were factored in, the project became two reversible lanes. This represents a unique design in the Atlanta area.

The I-75/575 project began in 2000 as a proposed extension to an existing HOV lane. In 2004, GDOT received an unsolicited proposal (which has also occurred in a number of other regions). A contract was awarded to a design-builder in 2006 based on prevailing state delivery legislation and was cancelled in 2009. A legislative bill then moved the project forward as a P3 concession agreement. The selection of a concessionaire took place, and an agreement was near when the governor cancelled the project in December 2011 because he felt that the financing and duration provisions of the P3 concession were not in the best interest of the state. The project then moved forward as a public-private DBF procurement with the developer responsible for 10 percent of the financing and public agencies responsible for the rest. The contract was executed in November 2013. Construction began on the project in the fall of 2014. These successive stops and starts were driven by a wide range of political, financial, legislative, policy, institutional, and design-related influences representing a learning curve in how complex, large managed lane projects get implemented. This experience was unique to GDOT but not necessarily unique among other managed lane experiences described in other case studies.

The lowest cost and least environmentally intrusive method to implement the I-75 reversible roadway was on the west side generally located within existing right of way. Transit service improvements are included as part of the project, but they do not require any transit-specific design treatment.

The I-75 South managed lanes are a design-build project without any P3 financing. This project was developed as a mechanism to reduce congestion on a critical section of I-75 south of Atlanta and apply tolling to help finance its implementation. Selection of a design-build provider was made under the state's conventional bid process. This roadway alignment is being implemented within the median of I-75. A reversible-lane solution was influenced by earlier selection of reversible lanes for the I-75/575 corridor, but no other reversible designs are envisioned in the region. Additional right of way was required for drainage retention basins, but otherwise, the project was accommodated within the existing right of way.

Design challenges faced on both projects were cost and right-of-way requirements, which would have been similar to any other general-purpose widening project involving the same level of investment. Both projects reflect a reasonable cost for the lane-miles provided, and direct-connection ramps are provided where the added capacity terminates into the Beltway. Design parameters called for utilizing existing right of way and minimizing bridge widening. Interchange structure replacements or modifications were minimized by taking flyover ramps over them. Shoulders and lane widths were reduced in some locations.

Multiple cross-sections were evaluated before a design decision was reached. For two-lane sections, a 10-ft shoulder is planned with two 11-ft lanes and a 4-ft outside shoulder. This design generally will fit within available right of way. For the I-75/575 project, one-lane reversible sections will have a 10-ft inside shoulder, one 12-ft lane, and a 4-ft outside shoulder. At isolated sections on I-75/575, the 4-ft shoulder will be reduced to a 2-ft section. On I-75 South, narrowing of shoulders will occur around gantries and gates. Channelized ramps will apply 5-ft shoulders on both sides of the barrier (see Figure 53 and Figure 54). Traffic will be able to always pass a disabled vehicle with these shoulder allowances. No specific local standards of practice were developed for reducing shoulder and lane widths.

Design speeds for both projects will be either 55 or 65 mph depending on the segment. A reduced design speed will be applied at some curves and superelevations. Design exceptions were granted for narrow shoulders. In retrospect, some of the GDOT design specifications provided to the P3 developer identified as "should" should have instead been "shall" to strengthen the specifications and improve the operational performance of the project.

Operation policy was established stating that no large trucks would be allowed in the express lanes. This decision was influenced by (a) allowance for 11-ft proposed lane widths in some locations, (b) pavement design cost savings to be achieved by restricting weights, and (c) improved surveillance since trucks block the view of cameras. Future managed lanes will require the same basic operation concept involving registration of all vehicles and electronic toll collection. A minimum toll rate will be applied to ensure collection cost recovery.

Source: Fuhs

Figure 53. Example channelized ramps from a comparable project in Seattle.

Source: Fuhs

Figure 54. Another example of channelized ramps from a comparable project in Seattle.

Separation Treatment

Concrete barriers and gates will be required due to the reversible operations on both roadways. Other projects reviewed prior to making these design decisions involving separation, access, and traffic control devices included the Selmon Expressway in Tampa, Florida (an elevated reversible roadway), and reversible HOV/HOT lanes in operation and development throughout Virginia.

Access

I-75/575 will employ local interchanges with arterials to access the express lanes. Flyover ramps will be provided to I-285. Channelized directional access ramps will be provided to/from the GP lanes. Safety concerns were mitigated by having a channelized barrier separation between separate entry and exit ramps. To improve driver expectations, the facility will never operate both entrance and exit ramps in the same proximity. The southbound directions from I-75 and I-575 will start as added lanes and transition to an existing HOV lane beyond the flyover ramp to I-285. The northbound direction will begin from an existing HOV lane and flyover ramp from I-285 and will terminate as a lane drop from the left.

I-75 South express lanes will also have grade-separated flyover ramps with I-285, an access with a new local interchange and channelized, barrier-separated slip ramps with the GP lanes. The northbound direction will transition into existing GP lanes; the southbound direction will end with a lane drop from the left. All reversible ramps will be gated.

Signing and Pavement Markings

Given the reversible nature of the design, “open” and “closed” notifications at all entries are critical. Side-mount signs will be used on the arterial intersections, and GDOT standard signs will be applied on the mainline. Dynamic signs will provide the prevailing toll rate to three

downstream destinations on I-75/575. For example, the display on the northbound I-75/575 project will include the toll to the next access point, the toll to the last access point on I-75, and the toll to last access point on I-575. The southbound direction will post the toll to the next access points and last access point. On I-75 South, two downstream destinations will be posted—the next and last access. Signing was designed to be consistent with the I-85 Express Lanes. Design decisions for signing were a joint effort between GDOT and SRTA. GDOT standards were maintained in terms of sign crowding and structural support. Slight variations in the location of toll signs were jointly developed to accommodate GDOT requirements.

Enforcement, Maintenance, and Incident Management

The projects' operation policies will limit the level of field enforcement required. Both projects will require all vehicles to have transponders, with no discount for free trips given except to transit vehicles that are easily detected by the tolling system. Toll enforcement will be handled using a video violation system. Speed and safety enforcement will be conventionally carried out by the appropriate law enforcement agencies as needed. The cross-section will allow for stopping violators in the shoulders.

Provisions for maintenance zones were taken into account in developing the final design. Some specific design treatments were adopted to address maintenance in restricted-width settings proposed on both projects. For example, a revised drainage grate based on a design from Florida was adopted into the roadway design to improve drainage efficiency.

GDOT policy for a major facility such as I-75 South is to maintain two operational lanes during inclement weather events. How the managed lanes will fit into this scenario has not been developed. Maintaining elevated portions of the managed lanes during winter icing conditions could probably lend priority to maintaining the GP lanes first and closing the express lanes.

A major requirement for maintaining express lane reliability was 100 percent camera coverage, which was included in the procurement contracts. Based on an I-85 experience, additional cameras beyond those needed for incident management will be provided to improve visibility and redundancy. This is due to the need for some cameras to focus on an incident while the toll operator (who is not located in the traffic operation center) can view signs to make sure that the posted tolls are properly displayed. The backs of all signs will include a flat paint to reduce glare when the reversible lanes are being used in the opposite direction to that which the sign is pointing. The projects will include emergency access gates located at approximate 1-mi intervals. The gates were specified based on early dialog with emergency first responders. This dialog included insight into how various types of responses (i.e., police, fire, ambulance) are dispatched.

Tolling System

The primary goal of the tolling system will be to maximize vehicle throughput while maintaining a high degree of accuracy in toll collection. Tolling gantries will be located near the entry and exit points. Full generator backup will be implemented to ensure toll collection

capability in case of a power outage. SRTA is charged with tolling operations, and it led decisions related to mounting locations and heights. GDOT is responsible for other traffic control devices such as gates and dynamic signs for relaying traffic messages. Both projects will use overhead gantries based on GDOT standards. The respective contractors are allowed to use existing sign structures if appropriate, per the procurement specifications. Both managed and GP lanes will be instrumented for data collection, which is intended to serve a variety of toll and traffic management functions.

Transit

Expanding transit use in the Northwest corridor was a significant goal. Design provisions for transit will be focused on off-site park-and-ride lots planned in the future as part of the projects. Access locations allow for transit services to access and use the express lanes. A proposed park-and-ride lot project has been coordinated with the I-75/575 project design.

Lessons Learned

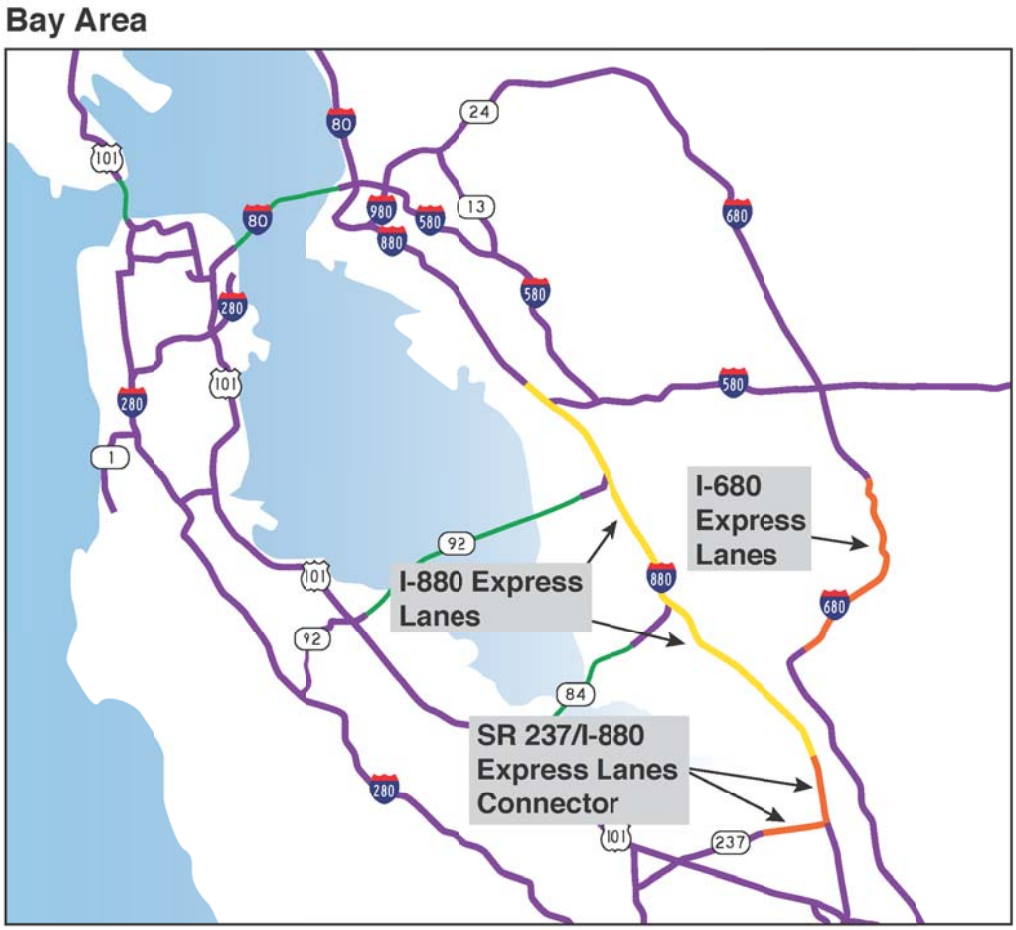
- **Public partnering.** Close coordination is critical among the local partnering agencies. Each brings unique capabilities and resources. In this instance GDOT provided civil and structural engineering expertise; SRTA brought tolling, operations, and financial levering/contracting expertise.
- **Design specifications.** In design-build and P3 procurements, tighter control of specifications and requirements is needed, based on initial experiences. The design specifications in some cases identified as "should" should have instead been "shall."
- **Tolling system.** Given rapid changes in technology, better clarity is needed in procurement documents for elements that need a technical specification (such as a gantry) versus items that should have a performance-based specification like the toll reader.
- **Peer-to-peer adoption.** Design decisions are based on both the parameters and constraints the team is given. In the two corridors receiving new capacity, there were opportunities to provide this capacity in a creative way and still largely stay within the right of way. Best practices were sometimes borrowed from similar projects and procurement approaches, in this case Florida and Texas.
- **Alignment preferences.** In very constrained portions of the I-75 North corridor, the best design solution was to go with an elevated alignment. This approach helped avoid modifications to the I-75/285 interchange and provided for high-speed flyover ramp connections.

SAN FRANCISCO–OAKLAND–SAN JOSE BAY AREA REGION

Background

The San Francisco–Oakland–San Jose Bay Area has an extensive HOV lane system that has historically operated part time and thus reflects a contiguous design in which the inside lane operates and looks like a general-purpose lane outside the restricted period. Most projects are operated with restrictions for 2+ HOVs, with I-80 and some ramp and toll booth bypasses operating with a 3+ restriction. Other eligible users include motorcycles and low-emission

vehicles permitted by the state. Numerous gaps exist in the system. Feasibility studies for operating the system as express lanes began in 2006. Based on these studies and experience from the region's first HOV conversion project on I-680 southbound, an express lane system plan has since been adopted and is in the process of being implemented. There are various projects in operation and development at this time. This discussion focuses on the operational I-680 and SR 237/880 connector projects and development of the I-880 project (Figure 55). An initial 800-mi system was envisioned, of which about 500 mi are currently planned based on costs and anticipated funding.



Source: TTI

Figure 55. Express lane projects in the Bay Area.

Agency and Project Context

A large number of agencies are involved in express lane planning and project development. These include Caltrans, the Metropolitan Transportation Commission (MTC), and a number of CMAs including Alameda County Transportation Authority (ACTA), Santa Clara County VTA, Contra Costa Transportation Authority, and Solano Transportation Authority. The California Highway Patrol also plays an active role in providing input to design and

enforcement of the HOV and express lane projects. The Bay Area represents a wide degree of autonomy in how projects get implemented.

Caltrans is the owner/operator of the freeway system. Various disciplines/departments involved within Caltrans include traffic operations, traffic safety, design, structures, environmental, and project management. Both the local district and headquarters staff are involved in most aspects of design decisions. FHWA is involved in reviewing key documents like the concept of operations and system engineering management plan documents. CMAs are self-help agencies with their own sales tax base to sponsor and contribute funding to the development of express lanes. Most of the express lanes in the Bay Area are locally funded projects. The local sponsoring agency provides funding, and when this happens, the role of the sponsor is significant, on par with Caltrans. In many cases, CMAs are the primary sponsors behind these projects and, through agreements and policies set forth by Caltrans, pay Caltrans staff for planning, environmental, design, and construction management services.

Sponsorship evolution has occurred over time. Caltrans was instrumental with advancing many HOV lane projects decades earlier. As of 2015, the CMAs are the express lane project developers. In addition to MTC spearheading express lane regional planning and implementation of some projects, it is also handling toll collection and account management for other regional agencies. This role dovetails with its role in collecting tolls for most of the area's bridges. This acknowledgment of roles and sharing of responsibilities is key to moving projects forward.

Reaching decisions on practical design has been locally difficult in this multipartnered environment. State policies and Caltrans design manual guidance involve many desirable attributes that are not always practical when the project or its tolling components must fit within the travel way or available right of way. Modifications are required, such as accounting for enforcement observation areas in the median. Such restricted design settings force Caltrans and CMAs to rethink how to consider prior HOV design exception approvals. This typical process involves determining how much to build to full design standard, analyzing costs and impacts, and determining when meeting adopted state design preferences becomes cost prohibitive.

The perception among some that excess revenue can pay for the cost of meeting standards has impacted how design trade-offs are considered and evaluated. Some decision makers may perceive that the improvement generates enough money so that what has previously been cast aside as cost prohibitive is now affordable. In general, such constrained settings do not accommodate full design standards. Some progress has been made to change attitudes, but local practitioners are still learning how such projects can be affordably developed.

Express lane system goals are to provide travel and reliability benefits and improved management to sustain mobility. Projects are dynamically priced and operated free to HOVs and transit. Implementation to complete the system will involve both conversion and new construction to address current gaps within available right of way. Most designs are single, concurrent lanes located next to the median, mirroring current HOV lane design. A few projects in Santa Clara County are proposed to be operated as multilane, bi-directional,

buffer-separated facilities. Available right of way, environmental, and funding constraints limit the level of capacity that is available to implement projects. Design is most influenced by availability of right of way and funding. The physical limits for conversion projects are generally established by traffic operation needs and project budgets.

Various challenges have been faced in moving the system forward:

- **Defining the project.** Determining how conversion projects (i.e., those that involve adding tolling to an existing HOV lane) are treated in the project development process has posed the greatest challenge. This appears to be an executive-level issue that influences the evaluation steps needed to address whether the project has minor or major impact. Funding and right-of-way limitations usually drive decisions on the scope of the project. Scopes have had to address many design exceptions in order to meet these limitations.
- **Evaluation procedures.** Clarity is needed on how to evaluate express lanes, which has primarily been a Caltrans role. A Caltrans-prescribed safety analysis, in particular, has been a stumbling issue that adversely impacted schedule and budget because technical staff did not know to perform it. Requirements have changed, and the process has evolved but has not been simplified.
- **Forecast revenues.** Disagreement regarding the amount of anticipated revenue is creating difficulties in reaching design decisions and agreements for revenue sharing among participating agencies.
- **Institutional and policy issues.** Various issues have both helped and burdened partner agencies. These issues include a Caltrans Traffic Operations Policy Directive (*2*), agreements with the California Transportation Commission (CTC) on projects, and local legacy policies regarding hours of operation and HOV-free use. Internal conflicts among agency divisions have cost time and money, particularly given the system-wide impacts when extrapolated to over 400 or more miles of proposed regional projects. A lack of hard and fast policies, such as safety lighting for continuous open-access designs, has presented challenges.
- **Project management.** Champions are needed within the partnership arrangement to move projects forward. Some topics, like a system-wide decision on open access, had champions at the Caltrans district level, which facilitated approval.
- **Consistency.** A lack of consistency is found in local/state guidance and in obtaining decisions from one similar project to the next.
- **Environmental streamlining.** A need exists for HOT lane conversions to be eligible as a categorical exclusion (CE) by their nature. In the last 15–20 years, the transportation practice has moved away from studying whether such operational changes are categorically exempt. If the scope focuses on operational improvements to a single lane on a freeway, the environmental requirements should be very straightforward. The nature of such a change is the same throughout the United States. Conversions commonly are limited to signs advising users that tolls are collected. If there is socio-economic sensitivity, this needs to be considered. In the local context, the CE process has become complicated, resulting in schedule delay and an increase in project development cost. In one example on a conversion project, placement of a communication conduit within the freeway right of way involved the

U.S. Fish and Wildlife Service because it passed through an environmentally sensitive area.

- **Partnership interfaces.** The involvement of multiple partners is positive in terms of expanded resources, but this can only be a benefit if the roles among partners are clear and understood. Tolling and operational management has shifted to the local CMAs since they manage demand and accounts. However, the CMAs do not have the authority to own or operate the roadways upon which the express lanes are located. Cooperation has not always flowed easily.
- **Technological life cycle.** Embracing and adopting the rapid pace of changing technologies, whether they are toll, connected vehicle, or traffic operations based, does not fit easily into the public agency project development paradigm. The evolution of technology is much more rapid than in the past. Public agency operators are challenged as change progresses more quickly than the technology's anticipated life cycle. As an example, local and state agencies have moved from legacy transponders to switchable tags that allow carpoolers to self-declare in order to get a free or discounted toll. This transition may evolve yet again when mobile apps are embraced. Each evolution has high up-front costs, interoperability challenges, and updated signing needs.

The regional express lane design vision has changed based on experiences on I-680 and from evaluations that better illustrated the costs and impacts associated with transitioning from the current HOV design with open access to an express lane design with restricted access. Initially, the concept design was to be a buffer-separated system with restricted access every 3 to 5 mi, similar to HOV lanes in southern California and HOT lanes elsewhere. Local user preferences for open access and desires by the Oakland Caltrans office (District 4) to maintain this approach showed that the express lane design concept needed to keep as much of the HOV design as possible. This decision was also influenced by parallel design decisions made on the Los Angeles express lanes to keep the legacy design and operation intact. Design parameters now involve the express lanes being as open as possible with access. Restrictions are only implemented where justified. These decisions were made at a network level. The following offer details for projects being developed and operated.

I-680 Express Lanes

I-680 southbound opened in September 2010 as a restricted-access express lane operated southbound to tolled SOVs and free 2+ HOVs under sponsorship of ACTA and Caltrans. Modifications being made in 2015 also involved sponsorship from the MTC. I-680 was the first buffer-separated facility in the region, so it was designed with separate ingress and egress locations to reduce weaving. Two toll zones were provided. After a more in-depth evaluation of the project's performance and feedback from the users, sponsoring agencies agreed to change the access policy and revert to open access instead.

A project in development will convert the existing northbound carpool lane to an express lane and make access modifications to the current southbound express lanes project. The upgraded design will not have designated buffers. Open access is going to be applied in both directions except in high-weave locations where buffers are added to improve operations. The project

applies variable toll message signs for dynamic pricing. The project limits stay the same. Typically, as a local practice, the HOV lane (and express lane) will terminate into a general-purpose lane and farther downstream a general-purpose lane is dropped on the right.

Environmental work including the safety analysis for the northbound I-680 Express Lanes took over two years, and design took 13 months. One of the hurdles to meeting the schedule was scoping the project and determining what was needed and attributable to the express lanes.

SR 237/880 Express Lane Direct-Access Connector

The first tolled express lane project to connect two facilities together on different freeways with an access ramp occurred in Santa Clara County under sponsorship of VTA and Caltrans. The connector ramp previously operated for HOVs between two HOV facilities. The main challenge was determining how to make the transition from HOV to express lane and back when the hours of operation were different for the corridors. Facilitating transitions in and out of the connector extended the project limits back for a total distance of several miles. Buffers were added at each end where access is restricted due to weaving. The project opened in 2012 to SOV tolled use and HOV 2+ free use.

I-880 Express Lanes

I-880 currently has HOV lanes, and it will also be a conversion in most segments. The 23-mi project reflects a longer distance than I-680 and includes more interchanges that need access restrictions to address traffic weaving. Between 40 and 50 percent of this distance will need to be access restricted. Restrictions involve approaches to interchanges and bridges. The corridor will have extensive median barrier-mounted illumination to address safety concerns by Caltrans.

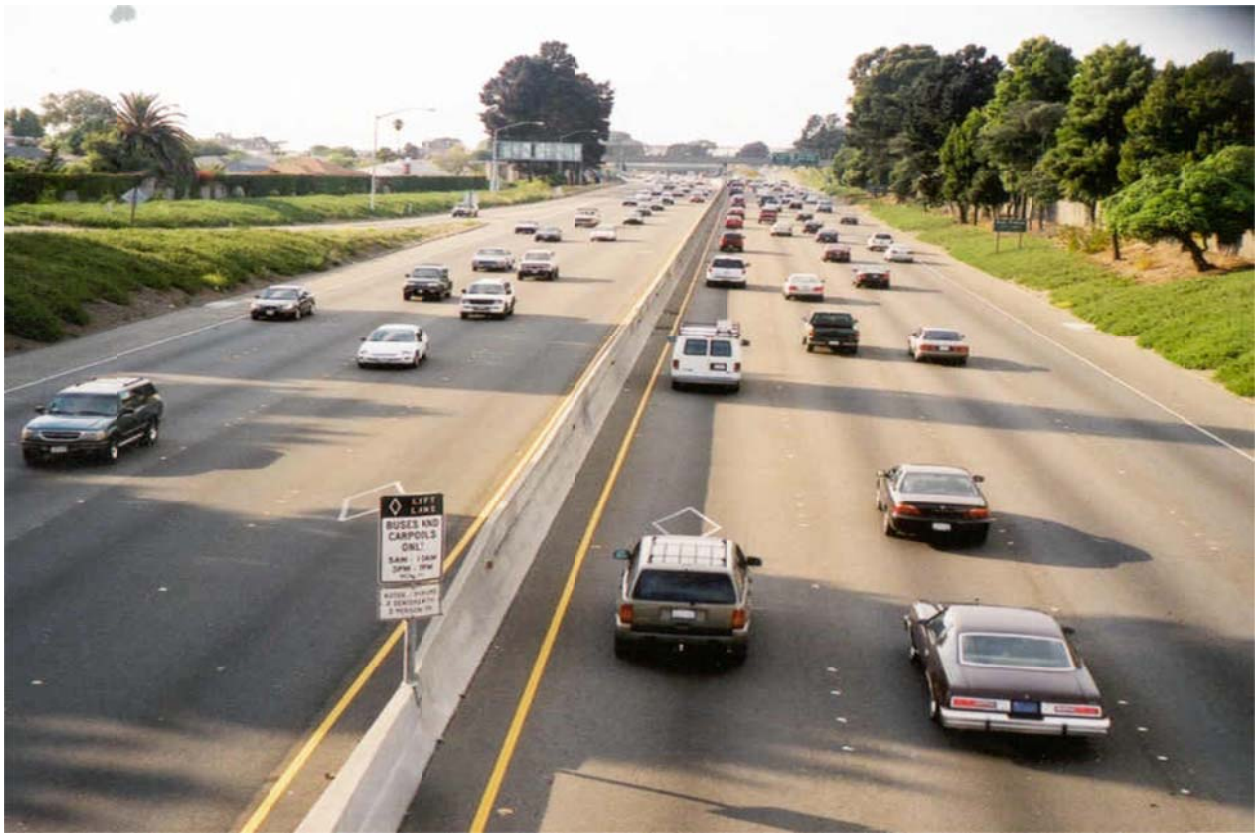
Overall Design

For Bay Area conversions, the design of the express lanes mirrors the prevailing HOV facility. Since many HOV lanes were created by consuming inside shoulders, the resulting cross-section varies from one segment to another. Most HOV lanes exhibit lane widths of 11 to 12 ft and left-side shoulders that vary from 4 to 10 ft (see Figure 56). Adding tolling will not change this design but will require signing, lighting, and pavement marking modifications.

Initially, the concept design for express lanes included a 2- to 4-ft buffer and access restrictions. Where HOV lanes do not currently exist, the new construction projects will follow prior Caltrans HOV guidance in determining acceptable trade-offs based on operational evaluations. Generally, the inside shoulder is reduced first, down to 2 ft, and then lane widths are reduced to no less than 11 ft. The outside shoulder width is rarely decreased for long segments, and if it is, emergency pullouts are considered. Determination of designated shoulder width involves applying tools and resources Caltrans has developed for making these decisions. Each project brings its own set of circumstances. Local practitioners

find it hard to get to a determination of a satisfactory compromise without extensive alternative studies.

Caltrans prescribes that a standard cross-section is a starting point in design with exceptions often grated where reasonable. A Caltrans-prescribed decision exception document is prepared to justify the reason and is based on the impact to build to standard, which includes impacts to right of way, environmental resources, and cost. The ConOps dictates to a large degree the resulting design. Design issues such as shoulder width, access, and tolling infrastructure influence the location, but the primary influence is the ConOps.



Source: Fuhs

Figure 56. Typical HOV design in Bay Area.

Developing the right solution to fit each context continues to be a work in progress. One practitioner offered the following perspective on addressing how design consistency is being treated for a given corridor and system:

> We have wrestled with a 2-ft versus 4-ft buffer separation in the Bay Area. There were some internal differences in opinion, so 2 ft is applied to be consistent. The whole evolution of what it means to be consistent is a question. The I-880 express lane project currently in development has all four of the [Caltrans] Traffic Operations Policy Directive design options in play. The temptation is to say this is pretty inconsistent. From

a driver's perspective what is going on? In one corridor this mix of designs may be inconsistent. But if we are sticking to the overall express lane concept, we are consistent with local standards of practice. The consistency becomes greater with a greater set of projects. But at local level it might not look this way. There is this balance between what people consider is consistent and what the operational characteristics tell you will work or won't work. What is a good standard? It is not uniformity throughout. Every design concept requires you to adjust to changes in traffic behavior.

Separation Buffers and Shoulders

Initially, buffer separation was required, but now the design will not include separation unless it is absolutely needed. For the I-680 project in development, ACTA and Caltrans started with a 4-ft buffer but ended up providing a 2-ft buffer. Evaluation of right-of-way constraints at certain locations necessitated going from 2 ft to 4 ft and back to 2 ft. A majority of the other planned projects do not have the width to provide a 4-ft buffer. No other form of physical separation is contemplated due to the restricted right of way on planned routes.

Access

Almost all of the HOV lanes within this region have been operated with open access, and safety has never been an issue. The University of California, Berkeley did an analysis (*225*) comparing the safety of buffer and continuous access and found no safety issue in operating with open access. Other designs were reviewed within California and experiences were drawn from locally generated white papers and comparative project plans developed by MTC based on national experience. Decisions for handling access at both the system and project levels were drawn from extensive evaluations involving all of the access types found in the Caltrans TOPD (*2*) and shown previously in Figure 1. These include separate ingress/egress ramps, weave lane, and weave zone, which is applied for open access. Based on local practitioner responses, comparative cost and signing requirements noted in the federal MUTCD, along with an increased likelihood for traffic microsimulation required by the TOPD, greatly complicate an express lane restricted-access design when compared to a more open-access concept. The preferred design for most but not all Bay Area partnering agencies is open access. This choice is also supported by driver familiarity on existing HOV lanes.

Going forward, the issue will be to justify where to restrict access, which becomes an exception to the overall concept of open access. Those decisions are being made based on a labor-intensive traffic analysis model. The evaluation becomes a balancing act that involves some iterations for VISSIM model results since the model in a supersaturated setting will be overwhelmed by other operational issues unrelated to the express lane. For restricted-access settings, providing access at every interchange is not practical, so some downstream destinations need to be combined to one access. Between left and right sides (and vice versa), Caltrans prefers at least 800 ft of weaving distance per lane. Where and how often to provide an access point will depend on traffic volumes and demand to/from a particular location. Generally, an access every few miles can be provided. If the interval is longer, it encourages buffer-crossing violations. If intervals are shorter, the express lane may not operate efficiently.

Signing, Pavement Markings, and Illumination

Tubular truss gantries are used for overhead signing. Sign structures and toll readers are designed for placement on flat areas without tight curve sections as much as possible. On I-680, MTC followed Caltrans's example of applying tubular instead of truss structures. Tolling information is posted for no more than three downstream destinations, and these signs were prioritized over other signing needs to reduce clutter. Access signing requirements were substantially reduced with an open-access concept. Side-mount signs include regulatory information (operation rules), distance to next destination, and, for access restrictions, a message reading "do not cross double solid lines.".

Some signing changes have already occurred to the I-680 Express Lanes. For example, southbound motorists coming from SR 84 upstream tended to quickly merge to get to the express lane prior to the start of the restricted buffer. This behavior caused merging and weaving friction on the freeway, so Caltrans added an upstream sign indicating that motorists have 1 mi to get to the express lane.

For these projects, practitioners follow the California MUTCD, which is slightly different from the national MUTCD. Caltrans, MTC, and CMAs discussed what was needed within the MUTCD guidelines, and after a few iterations, a final solution to be consistently applied on all projects was worked out.

Adding corridor illumination has been one of the more complicated topics addressed by the partnering agencies. Safety analysis results indicated a need for lighting where the median shoulder is reduced. For those locations, on curves, in access zones, and at toll readers, lighting became a project requirement. Getting closure on this topic required extensive dialog and evaluation. One project contains an agreement with Caltrans that MTC will install lighting within 1000 ft on either side of a pricing sign zone change, plus 1000 ft at the project entrance and exit. Designated access points are also included in this guidance. While lighting for I-680 is going to be located on the outside shoulders, lighting for I-880 will be placed on the median barrier since Caltrans already had a funded project to replace the median barrier. The lighting installations are so frequent that Caltrans will use custom hand forming instead of machine forming of the barrier to accommodate lighting. This condition will extend for more than 20 mi.

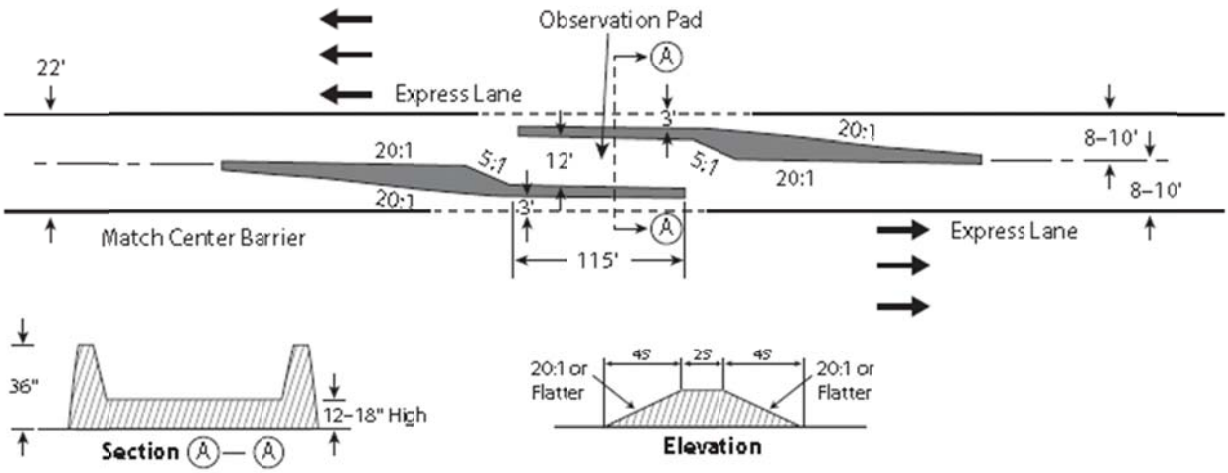
Enforcement, Maintenance, and Incident Management

CHP provided early involvement in the project initiation process and was heavily engaged during the design phase. Its tools for enforcement are changing since it is updating vehicle fleets from sedans to sport utility vehicles, and it is still employing motorcycles and cars for monitoring. Design provisions considered these changes.

Enforcement sites already existed on the HOV lanes, and these will continue to be used for express lane enforcement monitoring. CHP's practice is to no longer stop motorists in the left shoulder, so median enforcement areas have become CHP observation areas. Officers prefer

median shoulder monitoring locations located just downstream of each toll reader, with the shoulder semi-protected with an offset in the barrier, and an elevated parking pad so that they can see over the barrier in their patrol car (see example in Figure 57). To fit these areas into the existing 22-ft median, this width is redistributed by shifting the median barrier to create a minimum 12-ft space on each side with a residual 4-ft width on the other side. This practice of an alternating back-to-back observation area follows prior Caltrans HOV guidance. The observation area is typically 12-ft wide with a raised area for the CHP officer to park in. The raised area is up to 18 inches higher and offers improved visibility over the barrier. Barrier height remains 36 inches.

CHP officers view vehicle transaction status via beacons placed on the back side of the tolling gantry. A mobile app is also under development by MTC and CHP for improving enforcement. The new enforcement observation area approach was first deployed on the SR 237/I-880 connector, and it will be duplicated on I-880 and upgraded I-680 projects.



Source: TTI

Figure 57. Enforcement monitoring area.

Tolling System

Gantries supporting tolling equipment are typically single overhead structures with mast arms on both sides in locations with good visibility. Where the opportunity presents itself, both travel directions are addressed with toll readers on the same structure. Locations are based on traffic safety, operation, and proximity to major interchanges. Installation in flat areas in a tangent roadway section is preferred. Mounting equipment on existing overhead structures will occur in many locations, particularly for antennas that are otherwise hung from a mast arm in the median. Caltrans structure staff review and approve designs. Toll maintenance activities will require lane closures. Parking for maintenance is provided in the vicinity coinciding with need for an enforcement monitoring area. The projects will support self-declaration toll tags for carpoolers, but the system must also be able to read standard-issued toll tags.

CMAs operate different express lane projects using the same back office at the Bay Area Toll Authority, which is responsible for toll collection throughout the Bay Area. Currently, a separate operation center is located within each respective county for each project. Interest is growing in co-locating or sharing of operation centers. Most local agencies do not have the resources to staff each project on their own. An operation center that is regional could be more efficient; however, this consolidation is hard to achieve. A dialog is ongoing to address how to manage a regional express lane system with subregions wanting to control each project's revenue. A dynamic exists involving local, regional, and state control, with governance and operations in conflict. Meanwhile, the state administration in 2015 wants Caltrans to begin tolling new urban capacity projects.

Lessons Learned

- **Project evaluation process.** A better way for evaluating and implementing express lanes is needed, particularly for HOV conversions involving tolling. Practitioners must rely on their partnering agency counterparts to see projects implemented, but interviews reflected an uncertainty regarding each agency's roles, what type of evaluation is appropriate, and what timeframe (i.e., short- or long-range) made the most sense to focus on. The traffic analyses can take enormous effort and be a huge challenge. The analysis should be tailored to the intended impact and focused on the point in time when impacts are expected to occur. Some local practitioners have concluded that traffic simulation modeling, particularly in assessing future-year conditions, does not have the cost-benefit of informing the design in short- or long-term horizons due to the supersaturated nature of urban corridors when evaluating the impact of a single lane.
- **Agency partnering.** A goal of the project team should be to build relations and respect between partnering agency core resource competencies and identify what each can bring to the design process.
- **Funding transparency.** Decision makers need to be informed regarding costs and benefits associated with a project while grounding perceptions of revenue in reality. This understanding may help achieve a design outcome adjusted to these parameters.
- **Practical design.** Designers should be flexible in how design standards and the goal of design consistency is practiced and applied within a local project and for the planned system. Environmental requirements for operational changes need to be confirmed in the scoping stage.
- **Emerging/disrupting technologies.** An agency should prepare for emerging practices and technologies that have the potential to ripple through the project development and design process. The regional change in access preference is an example.
- **Legacy matters.** The project's legacy design and operation weighs heavily when forcing customers to adapt to operational and design changes. This recognition after I-680 Express Lanes opened helped agencies step back and reopen the lanes to a less restrictive access design.
- **Simple design.** The fewer the decisions motorists have to make, the safer the facility. Providing too much information on signs is a particular example.

- **Project delivery.** From a contracting standpoint, three types of procurements best capture the needs of an express lane system—general civil, toll system integrator, and back-office integrator. How these procurements support one another can be complicated if not properly specified. All contracts to date are based on professional service procurements, and this approach has worked fine. The toll integrator provides field design and installation. A separate back office provides operation and maintenance functions for all projects. Civil engineering aspects have been performed well in a separate, traditional design-bid-build process. One agency kicked off the environmental process with one consultant and anticipated a second procurement for design, but due to the frequent overlap, suggested combining these activities with the same procurement.
- **Sharing of infrastructure resources.** Sharing the communication backbone requires concerted efforts for agency partnering and addressing costs.

DALLAS–FT. WORTH REGION

Background

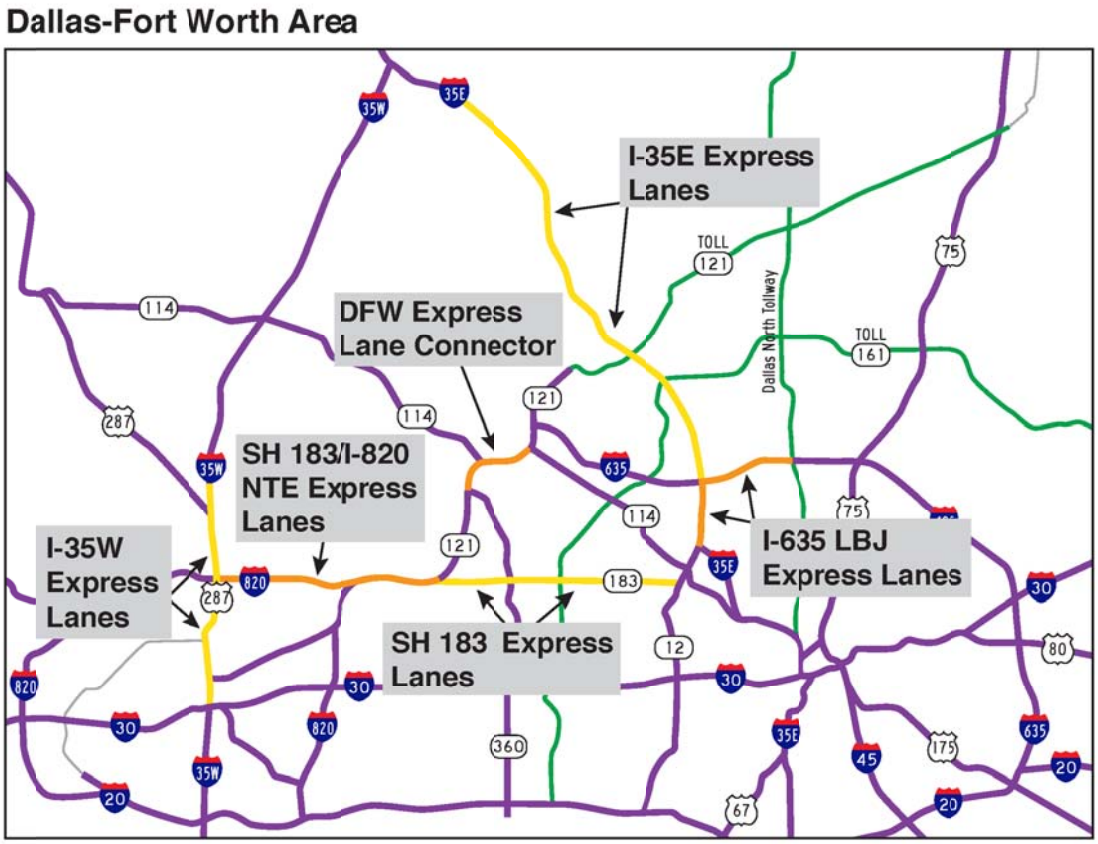
While HOV lanes have operated under joint partnership agreements for three decades in the Dallas–Ft. Worth area, a new initiative is to create a regional plan for a managed lane system and for tolling new capacity in congested corridors. This region now has the most expansive (and expensive) tolled express lane investment in the United States and will likely be one of the first to bring its plan to fruition. Corridors subject to this discussion are highlighted in Figure 58.

Agency and Project Context

The projects started out as added capacity expansion to address congestion management and air quality. Projects were developed as part of a regional plan. The Dallas–Ft. Worth area (Metroplex) is an air quality non-attainment area. Planning started in the early 1990s with the I-635 (LBJ) corridor since it was one of the most congested. The SH 114/SH 121 (DFW Connector) and SH 183/I-820 North Tarrant Express corridors were studied in the early 2000s. As a result of the study findings, regional planning has shifted focus from the air quality component to financial sustainability. Agencies needed to generate revenue to cover the cost of new construction if congestion was to be addressed. The original plan morphed from HOV to HOT to managed lanes over a period of years, but most routes comprising the plan remained the same. Initial projects from the 1980s were intentionally designed as an interim system of HOV lanes that could be upgraded and expanded. According to the original plan, permanent HOV lanes would be added to replace the interim projects. The plan largely involved single, reversible, barrier-separated HOV lanes and added GP lanes to reconstructed and upgraded freeway corridors. Adding GP lanes was ultimately reconsidered. As TxDOT embraced tolling as a policy for new urban freeway capacity statewide, a question was raised about combining the extra GP lane and the HOV lane to create multiple lanes that could be tolled.

The TxDOT policy did not influence the plan until 2006. The metropolitan transportation plan (MTP) from the 1990s was revisited in the HOV discussion to see how it could morph into a

managed lane concept and be financially viable. This is how the concept of managed lanes transitioned to what exists today. Regional direction and vision was changing. By the early 2000s, agency stakeholders realized that a policy was needed. However, enacting the policy prematurely would have made aligning demand with institutional, political, and financial realities more difficult.



Source: TTI

Figure 58. Express lane projects in Dallas–Ft. Worth area.

Agencies most involved in planning included TxDOT, NCTCOG, North Texas Tollway Authority (NTTA), Dallas Area Rapid Transit (DART), and FHWA.

- TxDOT and NCTCOG were generally the lead agencies in picking projects. NCTCOG served as the MPO for managed lane planning/policy, and TxDOT performed the implementation. The Regional Transportation Council (RTC), the policy body of the MPO, consists of elected officials who direct policy aspects of the MPO. They approve operation policies related to express lane and HOV rules and regulations.
- NTTA serves as the regional toll road authority and, by state legislation, has primacy for implementing toll roads in the Metroplex. It did not have this authority for implementing the LBJ project since it was created before local policy and legislation were enacted. NTTA has taken a greater role as more toll facilities in the region are implemented. TxDOT and Cintra perform the toll processing on the managed lanes

and send NTTA the toll tag identifications and amount to charge. Initially, NTTA did not have a role on express lane projects. Every non-NTTA project in this region has an agreement to collect tolls and manage accounts. Current arrangements allow NTTA to implement traditional toll roads and TxDOT to implement managed lanes.

- DART was initially a partner with TxDOT in building and operating interim HOV lanes on TxDOT facilities in five corridors around Dallas. DART funded some HOV lanes and operated all of them. When the region began express lane development, DART maintained HOV operations in some corridors, but as of 2014, it is no longer involved, and TxDOT now manages these lanes. DART continues to operate buses on HOV lanes.
- FHWA is the federal partner because tolling projects are on the interstate network. It has taken a lesser role locally since tolling has become mainstreamed.
- Several P3 concessions headed by Cintra US, which is part of the Madrid, Spain-based Ferrovial that serves as concessionaire/developer, also does the toll collection processing on the LBJ and NTE managed lanes. It sends toll tag identification and transaction information to NTTA.

After the interim HOV projects were operating, the first long-range project to be studied was the I-635 LBJ project. TxDOT's proposal was to widen LBJ without HOV lanes. The corridor involved an interesting mix of stakeholders. Neighbors around the project did not want any improvements, so they pushed for added lanes only in tunnels. This push-back limited opportunities for expanding the corridor or creating a high-profile elevated structure. Sentiments were based on prior US-75 North Central Expressway history from the 1980s, where TxDOT had initially proposed two elevated alignments for general-purpose expansion; TxDOT ultimately compromised on a depressed and modestly wider roadway that was less visually intrusive. Stakeholder sentiment echoed from this experience was "no higher, no wider" than the existing roadway. Making any widening concept publicly acceptable would have meant putting expansion underground. A nearby arterial tunnel under an airport runway had just been completed, so tunneling appeared feasible in the minds of local stakeholders.

As the LBJ project started to develop, local nomenclature changed from HOV to HOT and eventually to managed lanes. Operational aspects for managed lanes were determined on a corridor-by-corridor basis. Forecast HOV demand could fill up two lanes in each direction in the peak period. Meeting demand would have meant adding 10 GP lanes to the freeway, or the corridor would need to have six managed lanes (two HOV and one GP in each direction). The LBJ plan morphed into adding six tolled managed lanes to help offset costs associated with a tunnel alignment. That decision set the stage for the current regional plan.

Financing, limited right of way, and maintenance of traffic during implementation were the biggest challenges partnering agencies faced. Funding was adversely impacted by an LBJ tunneling concept. TxDOT did not have any legislation at the time that governed tolling. Subsequent policy changes at TxDOT for legislation that ultimately expanded financing and alternate delivery was approved as a direct result of the LBJ concept and difficulty in getting it funded and implemented. Partnering agencies were initially uncertain how they could toll an existing interstate corridor. Financing entire projects under design-build and P3 procurements ultimately made these projects feasible.

NCTCOG was brought in by TxDOT as a technical resource, and through this involvement, a natural, informal mediation role that the MPO could play developed. Various community groups were distrustful of TxDOT. NCTCOG could serve as this independent entity who could understand both sides of an issue. It already served a planning and regulatory role to ensure projects as approved by stakeholders and partner agencies were in the MTP. Both agencies always looked for ways to reach agreements that reflected both sides of an issue. Subsequent projects grew out of this newly formed relationship.

TxDOT's and NCTCOG's roles have been increasing with each project. NCTCOG's role and TxDOT's leverage through public- and private-agency partnerships keep getting stronger due to the financial ability to pick and execute projects together. Excess revenue allows for transportation improvements to be funded by local communities—to accommodate what they are asking for and have an available funding source. The RTC board reflects this perspective with a policy addressing how excess revenue from express lanes and toll roads is distributed—apportioning revenues based on toll customer addresses.

Projects now complete and operational include NTE Phase 1, DFW Connector, and LBJ Phase 1. Other projects being developed include the balance of SH 183 and I-35E from Loop 12 to Denton. The core managed lane system reflects two lanes in each direction. Some corridors will also have one general-purpose lane added in each direction. P3s were not found viable in some cases due to the economic crisis in 2008–2009, including the DFW Connector. Other projects were down-scoped to reduce debt. For example, SH 183 through Irving and I-35E to Denton will reuse existing pavement and bridges and provide one express lane in each direction for its early operational years. Political pressure to have improvements implemented quickly has also helped move projects along.

Unintended consequences occurred along the path to implementation. Some agency stakeholders are now experiencing toll fatigue. Work to convert HOV-to-HOT projects with DART was curtailed as TxDOT took over operation of the HOV system and finished a ConOps examining conversion potential. TxDOT was developing the US-75 corridor north of I-635 as a conversion when the project ran afoul of some county-elected officials who were against raising taxes as well as tolls on existing lanes and roadways. TxDOT has placed this project on hold until the legislature can find more statewide funding.

New financing and legislative tools, coupled with public agency cooperation and parlaying of public and private creativity, has greatly improved the ability to toll and finance express lane projects with less state/local contribution. Operation rules were changed to reflect this new funding reality, in which most HOVs, including two-occupant carpools, motorcycles, and low-emission vehicles, will pay a toll. Design decisions had to be balanced between implementation of the project in a timely fashion and the cost of the design on revenue. The "no wider, no higher" mantra from the LBJ experience has set parameters for all other corridors.

Design

The design setting varies depending on whether the project required full rebuilding of the existing roadway (i.e., LBJ and NTE) or widening (i.e., I-35E and SH 183 Irving). Existing pavement and structures were fully replaced on the former and were generally reused or modestly modified on the latter. Some structures date back to the 1960s. Right-of-way limitations and public attitudes toward widening forced designs like LBJ to become more expensive to finance and implement. The need to upgrade most of the existing pavement and structures on some routes helped move projects along, as did legislation allowing for P3s and design-build procurements. State and local policies helped determine how added capacity would be approved, and industry input helped agencies identify how projects could be financed.

The role of each roadway facility in a freeway corridor needs to be balanced. The frontage roads (FRs) handle local traffic, intermediate distance traffic is facilitated on GP lanes, and MLs serve longer trips. This understanding of how each facility meets different demands can provide something that will make all motorists and stakeholders happy. Finding the right solution for each of the corridors involves local government engagement in balancing both facility and demand needs. Within the affected cities, if more traffic can be accommodated on the frontage roads, there is less demand for the other roadways, and weaves are reduced. If the frontage roads are continuous with signalized bypasses, local traffic does not need to get on the general-purpose or express lanes. Every local government wants frequent spacing of interchanges. A balance between these roadways is required. Improving the frontage roads is key to making the managed lanes more efficient, which helps bring local communities on board. Determining access frequency and roadway connections is part of the dialog; it is not codified in local or regional policy. The more topics that get included in policy, the less flexible the policy becomes.

Many cross-sections were considered in balancing these roadway types. Some capacity may be provided free to each class of traveler, but local travelers typically benefit more when striking this balance. In the LBJ decision, no GP lanes were added, but frontage roads were improved. On NTE, future flexibility exists to add GP lanes based on the rebuilt cross-section. The DFW Connector has new capacity for everybody since it is an elongated interchange with major access at DFW Airport. As a result, the MLs are underperforming due to the added GP capacity. For the I-35E project, the philosophy was that all added capacity had to be tolled, so the initial footprint only adds express lanes. However, a county commissioner wanted a GP lane to be added as well, so both ML and GP lanes are being included rather than two MLs in each direction. Sometimes informed consent brings about awareness of what can happen now versus later. The balancing process determines what can be provided now based on cost and revenue. Timelines drive decision-making. When NCTCOG told local agencies that adding GP lanes would delay the project, they understood the trade-offs better.

Major interchanges were an impediment. Where columns cannot be negotiated, the mainlanes and direct ramp connectors fly over the existing multilevel structures. Such interchange flyovers exist at SH 183/I-820 and I-35E/I-635. Table 92 describes the basic design applied to each corridor.

Table 92. Facility characteristics associated with Dallas–Ft. Worth express lanes.

Project	Typical Condition	Access
I-635 LBJ (open)	3 lanes each direction , full design, barrier separation	Flyovers
SH 183/I-820 NTE (open)	2 lanes each direction, full design, barrier separation	Flyovers
SH 114/SH 121 DFW Connector (open)	1 lane each direction, full design, barrier separation	Slip ramps, flyovers
I-35E	1 express and 1 general-purpose lane each direction, full design, barrier separation	Slip ramps
SH 183 East	1 express lane each direction, reduced (interim) design, barrier separation	Slip ramps
I-35W	2 express lanes each direction, full design	Flyovers
US-75 North (HOV to HOT)	1 HOV lane each direction currently, reduced design, buffer separation w/ pylons	Limited weave zones

US-75 HOV Design

In the US-75 corridor north of LBJ, the initial plan called for a reversible HOV lane. The City of Richardson felt the off-peak demand in the morning would also justify bi-directional pylon-separated HOV lanes. In the final design, the city got HOV lanes in both direction, but no local access to them. The city did not want to pay for an elevated direct access because of the associated cost. Pylons were added to provide for some form of speed differential protection. This is the only project in the region implemented with pylons.

Project Delivery

Public Agency Perspective

LBJ was the incubator or test bed for implementing express lanes using alternate delivery. Once stakeholders warmed to this approach involving limited roadway widening, managed lanes were added into the other corridors. In most of these studies, the general-purpose solution was to add more capacity and include single or dual reversible HOV lanes in the median. Those studies exhibited a lack of foresight on how they would get funded and implemented. Legislation (House Bill 3588) changed this by requiring that any new capacity be tolled. Tolling was part of any lane additions to urban corridors. Throughout this process, TxDOT received unsolicited proposals for design-build and P3 teams. An unsolicited proposal was received for the LBJ corridor in 2001 before HB 3588 was enacted in 2003. The Texas Turnpike Authority (a division of TxDOT) at the time had the authority to build toll projects. Its board reviewed the LBJ proposal and did not accept it. However, that proposal foreshadowed how TxDOT would learn to procure and deliver projects through design-build and P3 options. Based on dialog with the industry in the early stages of procurement, the LBJ corridor and I-35 E south to Loop 12 were joined. The case was made that collecting and distributing demand was critical to financial return, so combining these corridors made sense. Dialog with the industry held as part of a letter of interest and procurement process determined that a concurrent express lane system serving demand in both directions 24/7 was

more financially viable than reversible lanes. Industry dialog pushed the idea that projects be self-financing. Projects had to be re-envisioned to new financial realities. The first P3 solicitation was cancelled by TxDOT based on responses received and reconfigured through a predevelopment agreement. Specific proposals, both unsolicited and eventually selected through a formal process, helped partnering agencies adjust the plan and project designs.

The Ft. Worth segments were all new-construction managed lanes. The NTE project was a $2.3 billion capital investment with a $600 million finance subsidy from TxDOT. LBJ had new tolled managed lane capacity and was GP capacity-constrained. LBJ cost $2.7 billion plus a $445 million TxDOT contribution. These projects guided public agencies' understandings of how projects could be closer to self-financing. TxDOT needed to configure projects to be geometrically, operationally, and financially feasible. This approach was radical for TxDOT engineers and required much give-and-take to develop the overall concepts, essentially reconfiguring the number of lanes, cross-section, alignment, project limits, operation rules, staging, and financing to meet these different feasibilities. Multiple steps were required in the solicitation (and learning) process, which took place over a number of years. No single approach was employed; some projects ended up being design-build and some were P3 concessions.

Comprehensive development agreements (CDAs) were a new tool applied to project delivery both in this region and throughout Texas. All of the projects in Table 92 except US-75 were or are being delivered either through a design-build procurement or a P3 CDA. TxDOT held tighter control than it had to on the first CDA agreements. Executing CDAs was a paradigm shift for TxDOT staff; they were not tied to the design but were tied to the outcome. Some design exceptions were involved at spot locations, such as getting the best trade-off for vertical clearance or sight distance. These clearances required approval from the TxDOT divisions and FHWA. The TxDOT divisions in Austin have generally deferred design decisions to the TxDOT Dallas and Ft. Worth Districts.

Three CDAs implemented in the region included NTE and I-35W in Ft. Worth (Phases A and B). These developers had more latitude than the TxDOT design-build for I-35E between Dallas and Denton. For projects like NTE, the Cintra team was able to quickly implement the project. The designs for NTE and LBJ were essentially finalized before TxDOT went out for procurements. TxDOT had to make sure each project was implementable and was consistent with the metropolitan transportation plan. To save time, the plan could not be modified. Alternative design concepts (ADCs), which allow private teams to propose alternate designs to the original concept, occurred after selection. An ADC was always measured to get the project completed faster and more cost effectively, relative to revenue impacts.

The biggest ADC was approved on the LBJ project. The original plan was a pair of tunnels, but the developer proposed a depressed alignment rather than deep tunneling, with a considerable cost and time savings. This change occurred during the proposal process. Another example is the direct connections between Loop 12 and LBJ, in which the P3 team proposed to open this segment by 2014 for faster revenue generation and not wait for the balance of the project to be completed. The P3 developer on the NTE project was able to change the originally envisioned design by bringing an elevated alignment back to ground

more often, resulting in reduced cost. Other ADC changes primarily involved alignment and ramp connections with adjacent roads with an emphasis on improved mobility. On LBJ, a substitution of a bridge connector with an embankment was proposed; however, it was rejected because it prevented visibility of businesses from the GP lanes. An ADC to improve the intersection with the Dallas North Tollway and LBJ was accepted. This ADC was an out-of-the-box idea that proposed moving columns of an existing bridge that allowed it to fit horizontal clearance for a different alternate roadway configuration. Another approved ADC was providing a new entrance and exit ramp to a neighborhood. A number of other ADCs proposed during the commercial close of the CDA were not approved because there were environmental risks that could have jeopardized the completion of the project. Opening the environmental evaluation due to ADCs potentially jeopardizes construction deadlines, particularly on a P3 project where revenue pays back the investment. Delays equal money lost.

Project limits were largely based on finance decisions to make sure project demand and revenue were in balance. The definition of the LBJ project was expanded to the west and south legs down to Loop 12 and dropped farther east along the LBJ corridor. The P3 or design-build team often provided input in this determination. The incentive for the P3 developer was financial (i.e., to start collecting tolls as soon as possible). Cintra had meetings at NCTCOG and TxDOT regularly to address policy, technical issues, and public outreach. The following testimonial during practitioner discussions sums up experiences from the CDA process:

> The variety of projects we are doing … are a collaborative effort—to get the projects on the board and on the ground. [We are focused on] how can we make it work. In the end, the public wins [with this approach]. The P3 partners may have gotten a good deal, but look what we got. [In our prior organizational setting] you couldn't move a stop sign without following protocol. It's a whole different ballgame when these changes occur on the managed lanes.

P3 Developer Perspective

The main challenges identified by the P3 developer to adding capacity were limited right of way, the need to maintain the same number of lanes through construction, and location of existing ramps and intersections. Limited space was available for improvement or modification to TxDOT's plan. A conceptual design, including tunnels, was provided by TxDOT, and opportunities were identified for improvement under the technical documents and outlined process. The result of a value engineering effort was a layout including a depressed alignment for managed lanes that fit the requirements of a "no wider, no higher" mantra. The Cintra team presented this ADC proposal, which improved cost, operations, and safety of the project. Value engineering was key in this process for large, complex projects. Design of ingress and egress ramps became a challenge due to limited space. Risks in negotiations were established differently for each project. TxDOT kept the right-of-way risk on LBJ, but not on NTE. TxDOT provided both projects with environmental clearance documents. Most of the risk of the project delivery was transferred to the P3 team.

Project limits were initially established by TxDOT. During the commercial discussions, Cintra proposed the possibility of opening the project in segments to allow getting some revenues and, therefore, make a better proposal to TxDOT since the incentive in the economical bid process was to reduce the public subsidy. TxDOT did not request intermediate milestones but accommodated the language to allow segment openings.

Separation Treatment

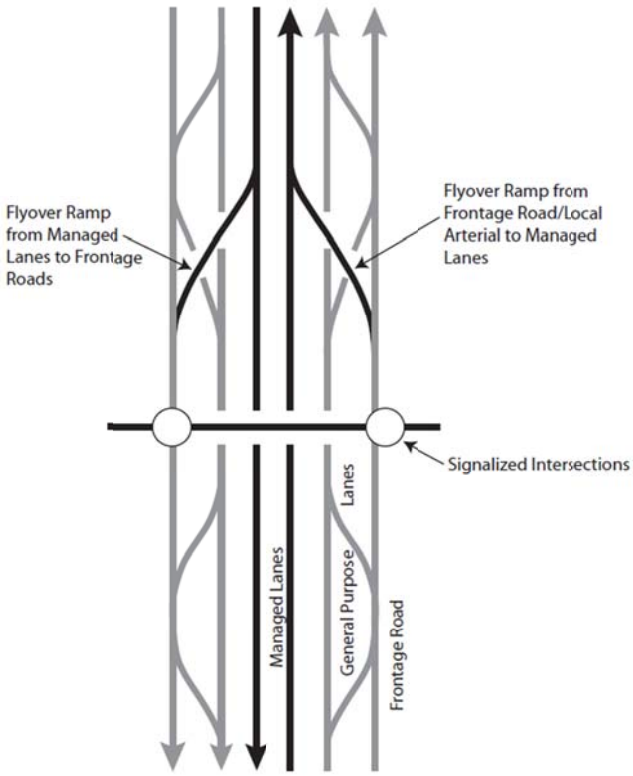
All project designs are barrier-separated with grade-separated access. NCTCOG and the Dallas and Ft. Worth TxDOT Districts strongly favor concrete barrier separation as a matter of design policy on express lanes. They consider this approach critical from safety and toll/revenue perspectives, and reconstruction of the corridors allows for this approach. A loss of productivity and toll revenue could result if lanes are not physically separated.

A challenge for the next phase of LBJ (east of US-75) is that this future conversion project is proposed to have pylons placed within a 5.5-ft buffer section instead of a concrete barrier. An existing US-75 HOV project currently provides a 1-ft buffer for pylons and adjoining 11-ft lanes with very little offset. These designs will inform operational experience when applying pylons within various buffer widths after both projects are converted and opened.

Access

A major element of the LBJ, NTE, and I-35W projects is the extensive investment in direct-access features. Managed lanes have direct access with the frontage roads to help reduce general-purpose lane weaves. Design of the roadway facilities has minimized weaving between MLs and GP lanes. At many locations flyover ramps take FR traffic directly into and out of the MLs (Figure 59). At major interchanges with other freeways, a separate set of flyovers provides these connections. One interchange now has 11 direct ramp connections counting GP and ML structures.

NCTCOG is now reassessing this access concept. With NTE now open, NCTCOG is observing that a subset of GP trips have to use the frontage roads to get where they want to go. This traffic travels through already overburdened signalized intersections to make the connection. Going forward, NCTCOG would like to see a broader mix of access treatment including at-grade channelized slip ramps between ML and GP roadways to address this need, similar to designs applied on the I-10 Katy managed lanes in Houston and elsewhere.



Source: TTI

Figure 59. Sketch layout of local access flyovers with managed lanes.

Signing and Pavement Markings

Managed lanes were integrated in existing corridors with frequent interchanges, resulting in space constraints for the placement of signing. Toll rates in the managed lanes are dynamic and can change every five minutes. These conditions require variable toll rate signs that have to be located before the last exit to allow drivers to make their decision depending on the prevailing toll. Tolls are different depending on whether drivers are a transponder holder or not and if they are an HOV or not, as well as on which of the five categories of vehicles they are driving since all vehicles are allowed to use managed lanes. Signing cannot address all of these different categories. Destination and base toll rates are given priority. All other categories of user tolling are not displayed.

No specific signage guidance was available regarding managed lanes in TxDOT guidance. The signage in the national MUTCD was not recognized by TxDOT for local applications at the time, and TxDOT Austin reviewers wanted a detailed assessment of signing both in Dallas and within their headquarters division. Consistency was a concern since multiple facilities were under construction on three corridors at the same time. Delays were incurred when attempting to reach agreement on signing the projects. TxDOT, NCTCOG, and NTTA had different preferences. NTTA did not like the sign concepts proposed by each developer or design-build team. Since NTTA was going to be sending customer bills, it wanted consistent signs. Local governments looked to NCTCOG to get this issue resolved. Coordination and consistency was required. The partner agencies went through two years of regular meetings.

Signing will always present a problem when there are different owners/builders for each leg of a system, and a priority is to provide regional consistency for customers.

A difference with signing still exists on each facility in the region. The state-operated facilities will display a pay-by-mail rate. The P3 concession-operated facilities will state "HIGHER RATES FOR NO TAG OR LARGER VEHICLES."

Enforcement, Maintenance, and Incident Management

Toll and occupancy enforcement represented the greatest needs for this region. Enforcement for separating discounted-toll HOVs from regular toll-paying customers was a concern in concept development. Initial concepts included separate lanes at toll gantries for monitoring carpools, but space was limited. For example, the I-30 project would have created three decision points to make this tolling enforcement design work. TxDOT coordinated with a tolling application provider to find a way for customers to self-declare on a website or with a mobile phone app. Collaboration with the technical designers, operators, and back-office people helped address this need. Financing for enforcement is the responsibility of TxDOT. Currently, HOV volumes are low, so enforcement costs are equally low. NCTCOG is responsible for paying an HOV subsidy back to the developer for free users, so it has more interest in enforcement efficacy than the project developer. The subsidy cost borne by NCTCOG for declared HOVs is low at this point, and about $18 million has been reserved to pay these costs. Local agencies will not adopt switchable tags due to cost and difficulty given the other interoperable tags across the state that are eligible on the managed lanes. The policy of the region's agencies is to treat occupancy enforcement and evasion as a toll management issue. If the system declares customers as an HOV, the only question is what toll they are charged.

Use of the beacon light positioned downstream of a toll gantry is applied to give enforcement officers knowledge of the toll paid for each passing vehicle. A wide enforcement shoulder is provided in these locations. Otherwise, a 10-ft continuous shoulder is provided, which is considered sufficient to monitor and apprehend violators.

No enforcement presence occurred early in design development, but enforcement was recognized as important. Looking back, TxDOT agrees that enforcement agencies needed to be engaged during the design process. Developers had to provide enforcement zones near the gantries for police monitoring. TxDOT has contracted with both local police and the county sheriff's office for enforcement on projects it sponsors. Other routine infractions are monitored by respective local police, and they are not paid on a dedicated basis for this traffic function.

The resulting projects typically reflect an upgraded design, so maintenance issues are lessened and not unique to managed lanes. A protected parking area is provided for maintenance personnel near most toll gantries with a barrier offset on the right (see Figure 60 and Figure 61).

Source: Fuhs

Figure 60. Maintenance parking next to toll gantry.

Source: Fuhs

Figure 61. Maintenance parking next to emergency gate.

The barrier offset provides an equipment pad immediately downstream of the toll gantry. Beyond the equipment pad, a parking area/shoulder that is 20-ft wide and about 100-ft long is provided. It serves as a refuge for maintenance parking and as a monitoring area for enforcement personnel.

Specifications call for the following maintenance life-cycle requirements in accordance with the P3 concession specifications:

- Concrete pavement design life: 30 years.
- Asphalt pavement design life: 20 years.
- Structure design life: 100 years.

The LBJ project has implemented an integrated the Roadway Weather Information System in the I-635/I-35E interchange to collect and relay local weather data to improve surveillance and post lane status messages to motorists. The projects have full lane and shoulder widths for all mainlanes and ramps, so removal and storage of snow would be the same as for any other urban roadway. Each roadway is drained separately, as would be the case for any urban design. No sheet flow drainage through barrier slots is applied. In many places, the profiles of each roadway (ML and GP) are different, and the separation barrier is a retaining wall.

Emergency Access Gates

A lack of communication and coordination with first responders had to be accommodated late in the design process. Future corridors being developed need to engage first responders earlier. For reconstructed corridors, emergency gates similar to those used on barrier-separated HOV lanes have been placed along the separation barriers. The gates roll open horizontally from a hinge fastened to one of the barriers. However, after installation was completed, some emergency vehicles could not fit through the opening. Gates were specified for passenger car evacuation, so they are deficient for larger and longer vehicles. A quick decision favored utilizing an off-the-shelf solution rather than thinking all of the possibilities through. The gate selection resulted in two issues—inability to meet EMS/fire needs and

inability to evacuate all traffic from the managed lanes under extreme conditions. First responders are required to block the inside shoulder and leftmost general-purpose lane to swing the gate open when providing access.

Tolling System

The tolling system was studied in a very detailed manner. Tolling is installed strategically with no specific frequency along the projects with the principle of not losing any drivers in the system. A pullout refuge is provided on the right side with a barrier offset that protects maintenance vehicles (Figure 60 and Figure 61). Factors for locating equipment included camera and reader visibility, ability to consolidate equipment (generators, batteries, and maintenance cabinets), and maintenance accessibility. Overhead toll equipment is mounted on one gantry. This decision saved cost with no impact on accuracy. Equipment was designed to reduce maintenance, so it can be fixed or moved and quickly replaced. Access is easy in most locations, although a few sites will require shoulder or lane closure to perform work. Urban highways do not allow much space for tolling systems and maintenance access. NCTCOG has a tolling plan for allowing two toll facilities to be interconnected with no allowance for exiting (i.e., escape in case drivers do not want to pay) between both facilities.

Lessons Learned

- **Regional policies.** Adoptions of regional policies have helped speed delivery and promote consistency. NCTCOG's philosophy is to incorporate managed lanes in reconstruction; however, less-than-desired designs are being applied for some interim projects. NCTCOG has extensive policies ranging from agency roles and responsibilities to excess toll revenue disbursement. However, they also recognize that flexibility may be lost with too much emphasis on policy.
- **Barrier separation**. All projects should be barrier-separated to look like a freeway within a freeway implemented as a corridor solution.
- **Projects planned as a system from the beginning**. Analysis of system-wide and funding/financing issues took the agencies longer than other locales, but through this effort, more miles will have been opened within the next five years than anywhere else.
- **Political support**. With their exponential increase in projects, sponsoring agencies are reflecting on how projects are implemented and the ongoing support they need. Some policy makers are new to this concept, and they may slow down this momentum. Practitioners will have to continue to make the case based on monitoring the value proposition and performance of selected designs.
- **A "freeway within a freeway."** Most of the managed lane design is within traditional freeway design practice, and there is little uniqueness being applied to managed lanes since they serve all users. Finding the best mix of access treatments and emergency evacuation should continue to be explored.
- **Agency partnering.** Collaboration of multiple agencies throughout the planning phase was a time-consuming effort. Once the developers started to build these projects and identified design issues, they needed the ability to make design changes.

Changes required a process and took time, but the partnering process and perspectives of each participant improved the overall product.

- **Knowledge sharing.** Practitioners at NCTCOG used to work at NTTA and TxDOT, so they bring different ideas to their new agency. Sharing of talent has improved decision-making and policy development.
- **Education and marketing**. Managed lanes are based on congestion pricing, meaning that the more the congestion, the higher the rates. This seems counterintuitive and can make customers and policy makers think that P3 developers are taking advantage of them, when the project is really providing a reliable commute to those who need it. Addressing the rationale for entrances and exits represents an essential need with affected communities along the corridor.

LOS ANGELES REGION

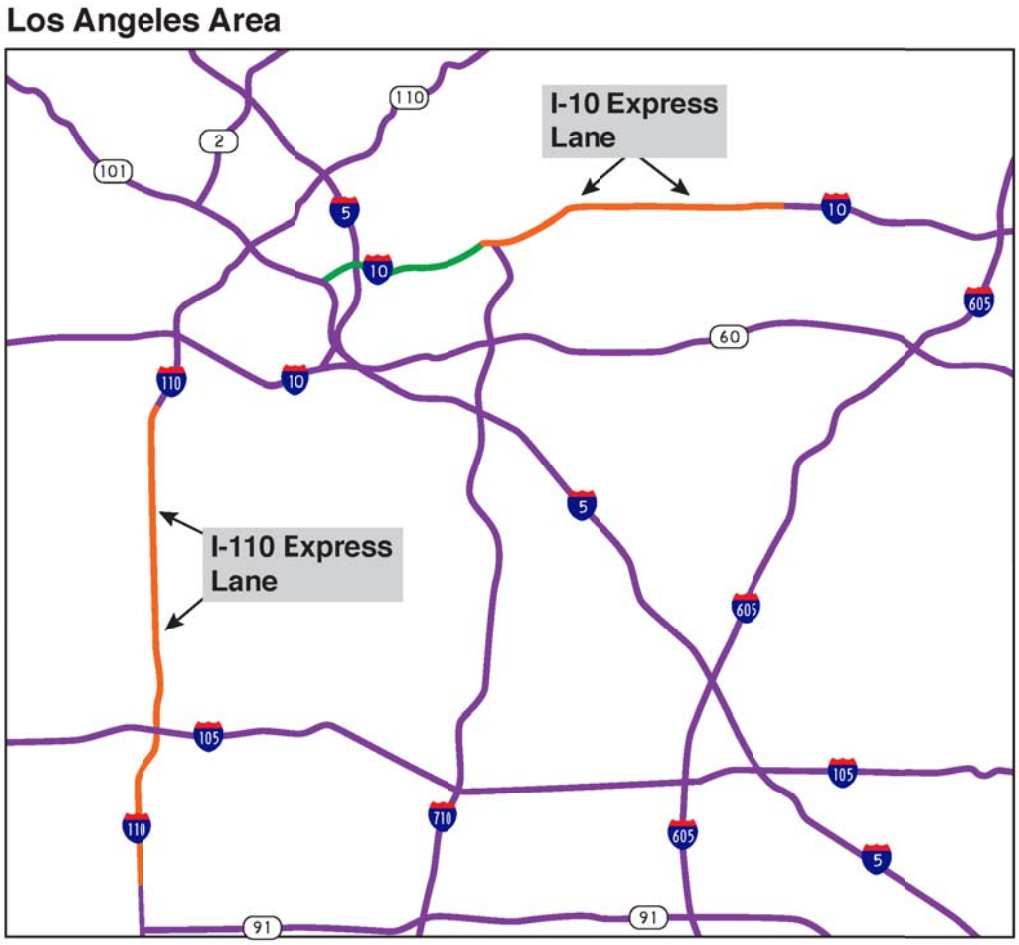
Background

The Los Angeles area, comprising Los Angeles, Orange, San Bernardino, and Riverside Counties, has more HOV lane-miles than any other region in the world. Accordingly, this area has a long legacy in deigning managed lane facilities dating from the 1970s on the El Monte Busway. One of the first tolled managed lanes was implemented on SR 91 in 1995. Since then, congestion pricing had not been demonstrated on any other regional facility until a federal grant was approved to demonstrate tolling in Los Angeles are as part of the USDOT CRD program. The original corridors proposed in the San Gabriel Valley were I-10 and I-210, but these candidates were changed early on to include I-10 and I-110 (Figure 62). These projects are the subject of this design case study.

Agency and Project Context

A wide range of mobility goals/objectives were associated with the simultaneous conversion of the I-10 and I-110 corridors. They included:

- Manage congestion by utilizing all available capacity in the transportation system.
- Integrate other modes to create travel options and modal shifts.
- Maximize corridor person throughput.
- Improve travel reliability.
- Be sensitive and address environmental justice concerns as part of the program.
- Test partnering and collaboration among sponsoring transportation agencies.
- Minimize impacts to legacy users, both in the HOV and GP lanes.
- Enhance the highway facility for better operation.
- Enhance/expand transit service in corridors.
- Address bottleneck locations.
- Integrate parking management strategies into the program.
- Address improvements as part of total corridor management.
- Manage expectations by managing performance.



Source: TTI

Figure 62. Express lane projects in greater Los Angeles area.

Challenges and needs agencies faced included:

- **Constrained design and operation.** Both corridors were supersaturated and difficult to manage with the available design. An absence of sufficient right of way limited options. A lack of enforcement areas along I-10 was particularly difficult to overcome.
- **Different conditions for each corridor.** The design of I-10 was quite old, while I-110 was relatively new. Roadway design, operations strategies, available capacity, and transportation options and service providers for bus and rail differed by corridor.
- **Environmental justice issues.** Demographics differed by corridor, with a relatively high level of disadvantaged communities. A consent decree affecting I-105 and its interchange with I-110 posed limitations that could reopen environmental rulings with this project.
- **Implementing improvements quickly.** The CRD federal grant had a condition of securing funding to implement the project within a tight schedule; thus, a conventional implementation timeline would not work. A setback in meeting schedule for I-10 incurred due to ongoing pavement maintenance work that was not

able to be accelerated. Luckily, the federal administrators of the program were flexible and did not penalize the project.

- **Staying within budget.** The project budget was fixed by the federal grant.
- **Contracting process.** Caltrans advocated for DBOM with incentives for early completion, but LA Metro had to be the contracting agency due to the terms of the grant.
- **Political support.** Elected officials at federal, state, and local levels viewed the concept differently with a wide range of expectations. Managing these expectations involved extensive coordination.
- **Modal balance.** The value of integrating other modes into the overall solution needed to be understood; this was not just about toll lanes. Funding emphasis was placed on transit services, stations, and parking pricing, which is not typically included in a tolling project.
- **Addressing design exceptions for an unconventional process.** The depth and breadth of design exceptions, procedures, review, and approval requirements were not fully understood or acknowledged by the entire team composed of diverse disciplines.
- **Lack of tolling experience.** Demonstrating tolling in a county that had no other toll roads represented a risk.
- **Enforcement.** The system needed a design that could handle enforcement effectively.
- **Speed differential.** Maintaining some form of separation and access restriction between parallel roadways was a concern.
- **Outreach and support.** Performing extensive outreach and education with the community organizers was needed to identify and address equity questions. Education, marketing, and promoting awareness leading up to opening was required to attract demand.

Opportunities that made the design challenges surmountable included:

- Providing a funding source, which was capped and time constrained, to help push decisions along.
- Having champions within both partnering agencies willing to work closely with stakeholders and seek common good.
- Demonstrating value or benefit to partner agencies including municipalities and transit agencies.
- Developing strategies and programs for each corridor that provided value back to community.

Agencies involved in this project included:

- LA Metro—Roles included program lead, contract implementer, and transit operator.
- Caltrans—As co-lead with LA Metro, Caltrans is owner/operator of the interstates and established operational and design requirements. Caltrans performed the environmental document for both projects.
- City of Los Angeles Department of Transportation—Project partner primarily involved in street and signal interface from express lanes and parking pricing program.
- Foothill Transit—Operator on I-10.
- Torrance Transit—Bus operator on I-110.

- Gardena Transit—Bus operator on I-110.
- Metrolink—Commuter rail operator for service in the I-10 corridor.

Caltrans (District 7—Los Angeles) and LA Metro were primary sponsors and key partners through design and project delivery. Design input within Caltrans came from Los Angeles (District 7) and the headquarters in Sacramento involving at least 10 points of contact. While Caltrans was the owner/operator of the underlying roadway facility, LA Metro was in charge of the program and was the primary CRD partner and manager of the financial resources. Caltrans had a cooperative agreement with LA Metro that compensated the agency for staff costs incurred. LA Metro performed the community outreach, established corridor advisory groups, and managed marketing. Caltrans provided construction inspection services.

The Caltrans design standards and local preferences were geared to new construction projects. For retrofit projects like HOV-to-HOT conversions, the culture and mindset for project review did not work well. New Caltrans design standards got adopted after planning and design was underway on these projects, so they did not get incorporated. Staff and local agency leadership within Caltrans and LA Metro were not able to wait for directives from Sacramento to incorporate the new standards. This inability to address the latest requirements created friction within Caltrans between local and headquarters reviewers. The local Caltrans project manager tried to address the policies set forth from the project partnering team, and this created an environment for internal agency conflict. The CRD funding required quick decisions, or the grant would have been cancelled. From a design standards perspective, the practitioners could not go back and retroactively include something that added cost and created delay without all partners having an understanding that such change could kill the project. Many design situations that were inherited from the legacy design had to be accepted as non-standard. Resolution sometimes had to come from upper management regarding trade-offs, and some had to be acceptable without extensive evaluation. Staff within Caltrans were guardians in keeping standards, but they could not be allowed to stop a project. One example was the I-10 terminus where the available width ended up being less than standard to fit within available right of way, and this required a design exception. A preferred solution was to extend the express lane upstream of the observed traffic queue at I-710 where the entrance was located. The design reviewers would not support the Caltrans project manager in this instance, and as a result, a new traffic bottleneck formed near this terminus.

The political process drove the project at an early stage. Local leaders tried to obtain federal grant funds from the original UPA project solicitation but did not have partners on board within the short timeframe; they were better prepared for the CRD proposal. For this project, it was important that political leaders not expect much congestion relief. In a highly complex, overloaded roadway environment, improved system management was a more likely outcome since I-10 and I-110 operations were beyond the goal of congestion relief. Improving efficiency required increasing people throughput and shifting demand to transit.

The state DOTs had the technical knowledge on highway design and operations. The regional agencies understood their customers better because they were closer to them. LA Metro had greater latitude than Caltrans on contracting and funding projects and being able to lobby politically for what is needed. Locals were also better adept at education and marketing. Each

partnering agency needed to respect and leverage each other's strengths. Coupling the best of both resulted in a better design product and operation. Two manager champions—one at Caltrans and one at LA Metro—ran the program. The Caltrans manager largely handled the technical discussions; the LA Metro manager handled the policy needs, outreach, and tolling systems since LA Metro was going to be responsible for collection and managing accounts. The agencies had to build their partnerships through technical staff with responsibility and authority from agency leadership. These agencies had not worked on jointly coordinating and building a project. Agency champions had to bridge these shortcomings between their different cultures and soften their agencies' positions to come up with solutions and agreements to keep the project moving.

Congestion reduction on the I-10 and I-110 HOV lanes was the first reason for the tolling system to be implemented. This intent is spelled out in the ConOps. Both corridors were suffering degradation from too much HOV demand, and benefits were being lost. Nobody at the policy or staff level believed these projects to be capacity enhancement or expansion. They saw this program as an experiment with congestion pricing to make the case that HOT lanes are a means to influence demand and achieve operational performance benefits. Demonstrating dynamic tolling was an important way of regulating demand. Minimizing impacts to legacy HOV and other eligible users drove the ConOps process. This policy issue was driven by the reality that in peak periods, the lanes would likely have to resort to HOV-only operation since capacity limited how many others could be accommodated. Operation assumptions included maintaining the same eligibility requirements for I-110 (2+ free) and I-10 (3+ free during peak hours), coupled with a new condition that each carpool carry a self-declaration transponder with a valid account. Caltrans and LA Metro also wanted to keep the same access locations.

Overall Design

I-10 Project

The I-10 express lanes extend from Alameda Street to I-605. Overall design parameters required staying within the existing right of way and generally within the existing edges of pavement, with no reduction of lanes and no access change. Adding tolling to I-10 and refiguring the roadway to provide two lanes in each direction was presented as a demonstration project with a limited life cycle. HOV restrictions would not change (i.e., 3+ occupancy requirements during peak hours of operation and 2+ at other times). Legacy HOV users had to be accommodated, so the redesign had to look similar to what users were familiar with.

The I-10 Express Lanes, formerly called the El Monte Busway, was operated as a single concurrent lane in each direction with a wide shoulder (Figure 63). Caltrans already had a pavement rehabilitation project underway to rebuild the roadway when the CRD grant was awarded. This reconstruction allowed for the opportunity to convert the wide shoulder/buffer in order to provide dual express lanes in each direction between El Monte and I-710. Except for one location on the west end, no outside widening of the roadway was required to accommodate the second lane. The existing buffer and shoulders were not sufficient to

compensate for the added lane, so widths of the GP lanes and shoulder were reduced. Accommodating full-width shoulders and lanes was considered but rejected due to prohibitive costs. Freeway overcrossings posed impediments. Trade-offs triggered numerous design exceptions. Most influential in this process were local Caltrans geometricians and operations staff and the FHWA program administrators from Washington, DC. For example, planned modifications of concrete barriers to current height standards at new dynamic message sign locations were not noticed until after project plans were approved. LA Metro was not receptive to accommodating corrections due to cost and schedule delays, so the prior barrier heights were maintained in spite of objections of some reviewers.

Source: Fuhs

Figure 63. Prior configuration of I-10 HOV lanes with wide buffer.

The resulting design could not accommodate 12-ft-wide lanes for buses. Caltrans tried to abide by the hierarchy described in the Caltrans HOV guide (5), which recommends the following trade-offs:

- Left shoulder reduced to 10 ft where possible (essentially only at a few spots).
- Buffer reduced to 2 ft.
- Left shoulder reduced to 8 ft.
- HOV/HOT lanes reduced to 11 ft.
- GP lanes (except the outside lane) reduced to 11 ft.
- Left shoulder reduced to 4 ft and then to 2 ft.
- Right shoulder reduced in spot locations where absolutely necessary.

I-110 Project

The I-110 transitway was a relatively new (1990s) four-lane buffer-separated facility (two lanes in each direction) with direct-connection ramps, online transit stations, and park-and-

ride lots over a 10-mi distance from SR 91 to Adams Street near downtown Los Angeles. The typical section includes a 10-ft inside shoulder, two 12-ft lanes, and a 4-ft buffer (Figure 64 and Figure 65).

Inside shoulders were reduced at locations where weave lanes were added to enhance the previous weave zones (see Figure 1), or at breaks in the solid pavement markings. Widening of the off-ramp and reduction of a shoulder at the North Adams Street terminus was implemented to facilitate flushing of off-ramp traffic and reduce queuing.

Source: Fuhs

Figure 64. Typical roadway design for I-110 (before condition).

Source: Dewey

Figure 65. Typical roadway design for I-110 (after condition).

Solutions Considered That Were Rejected or Deferred

- The I-110 project's northern terminus caused queuing as traffic entered the downtown street system. The extension of express lanes farther north was precluded due to limited right of way, likely environmental impacts, and cost, so the ConOps stopped at the project's northern terminus.
- On I-10, the viability of extending project limits farther east was deferred and, if warranted from further study, may be implemented if future funding can be secured.
- The idea of tolling all San Gabriel Valley freeways (I-210, I-10, and SR 60 as a corridor system) was dropped early in the grant negotiation process due to political issues and funding grant terms that would have allowed only one corridor in this valley to move forward. Transit service needs were more important for I-10, and no political will existed for multiple tolled corridors impacting the same commuter market.
- Eastbound I-10 ingress should have begun at City Terrace upstream of a daily queue. The decision to drop this improvement in access was internal to Caltrans and was influenced by design geometrics reviewers. Caltrans got the City of Los Angeles to agree to concessions but could not get approval internally.
- Elimination of some ingress/egress points along I-110 to improve operation and reduce friction was suggested. Several access points had low demand, which adversely impacted vehicle flow rates. A study was undertaken to address environmental justice concerns, and removal was perceived as a take-away to the local community. A design compromise retained the access and created a weave lane. The result was an auxiliary lane in a higher, denser traffic condition with loss of the inside shoulder.
- Concerns were raised about westbound buses merging onto the express lanes from the El Monte transit center, and a proposal to meter this ramp and another ramp was made. Sight distance issues were identified, and realigning barriers satisfied the original concern. Adjustments were made for some advisory design standards.

Sight Distance Issues

Horizontal curve sight distance issues were identified on I-10. Some prior conditions were not corrected, and Caltrans had to seek approval for design exceptions. Sight distance concerns at the easterly end required realignment of the concrete barrier.

Drainage

Since no change in route profile or superelevation occurred on either corridor, drainage issues were related to proximity of the travel lanes to barriers. Accommodating the additional lanes, except for I-10 EB at one location, was achieved by changes in delineation. The I-110 HOV median shoulder was reconfigured to accommodate weave lanes at access points. As a result, the new roadway became hydraulically deficient. Hydraulic analysis showed that a storm event might cause ponding beyond shoulders into the traveled way. To address this drainage

deficiency, a contract change was issued to install a $4 million drainage system along parts of the median.

Project Delivery

While civil and structural design changes were addressed conventionally with Caltrans oversight, delivery of the tolling system changed during the development process. At around the 30 percent design stage, LA Metro made a decision to move away from a conventional design-bid-build process to procure a DBOM team for the tolling and enforcement system on both corridors. LA Metro made this change from a contracting and risk management perspective. Its risk was reduced with a single contractor, and it had a tight schedule to meet. The DBOM team was responsible for all internal quality and all of its design calculations. Joint agency review of substructures and superstructures was performed by Caltrans and LA Metro. The DBOM team was allowed flexibility to determine what was needed and how to install tolling infrastructure. For example, pavement loops or sensors could have been applied, but each had to respond to reliable operation. LA Metro allowed the DBOM team to facilitate handling some functions remotely. Computer servers were based in New Jersey, and the call center was located in Utah. This was an appropriate decision since this operation was for only a one-year demonstration. Facilities located in closer proximity might be more typical for large, permanent systems. A separate conduit was provided to tolling installations for security. Caltrans fiber was used as a redundant backup system, serving as a loop if damage occurred to the tolling network.

The entire project inclusive of civil roadway, structures, and construction that opened to traffic was performed in the DBOM contract. The pavement rehabilitation contractor already on the I-10 corridor ended up being the express lanes contractor for the express lane civil improvements under the DBOM team. The design-builder for the toll system was not aware of how much the design exception process would play a part in getting the project built. This process was complicated. The DBOM team had to go through exceptions in accordance with Caltrans's requirements. Caltrans was responsible for internal quality assurance, and the DBOM contractor was responsible for overall quality control/quality assurance. From Caltrans's perspective, this arrangement presented a big challenge compared to how projects are typically implemented, yet it is utilized more and more on big projects where local (non-state) agencies have the lead.

Separation Buffers and Shoulders

Painted buffers were applied on both prior projects. I-10 had a wide buffer, which became narrower with the additional express lane, and the I-110 corridor had a 4-ft buffer. Except for the buffer width on I-10, special delineation details employing two solid white stripes with markers were used. The design had to account for limited funding, space restrictions, and need to maintain driver expectation consistency.

Pylons were not considered for the following safety-related reasons: (a) close proximity to travel lanes that would cause hits on pylons if they were installed; (b) increased maintenance

activity to repair or replace pylons; (c) risk to highway workers while maintaining pylons; and (d) lane closures required to facilitate maintenance of pylons.

Shoulders vary considerably, with most of the I-10 inside shoulder being about 2 to 4 ft. The I-110 inside shoulder is 10 ft except at weave lane locations, where it is 4-ft wide.

Access

No major alterations were made to the preexisting ingress/egress locations. As a result, no operational studies were performed. The I-110 express lanes (both northbound and southbound directions) are the innermost general-purpose lane at the termini. The westbound I-10 express lane ends at Alameda Boulevard. The eastbound I-10 express lanes become the innermost general-purpose lane.

Signing and Pavement Markings

Due to the age of signing on I-10 and I-110, most existing messages and nomenclature did not meet the latest design standards, and most had to be replaced anyway. Two downstream destinations are typical on pricing signs and include the next major access and end of facility. Various agency staff were involved in determining messages. If the lanes are closed for maintenance, one message is displayed; if the lane has an HOV-only restriction, a different message is displayed. The project team spent much effort figuring out what message to display for different conditions. One change needed soon after opening was clearer communication for free carpool use. The message "HOVs free" was changed to "HOVs free with FasTrack" (transponder). Other important messages included posting occupancy requirements in conjunction with hours of operations on I-10. The projects tried to follow the federal MUTCD recommendations for overhead signing. Existing sign structures were used in many cases. On I-10, various sign panels had to be realigned to match the new lane configuration. The projects required installation of a hundred new overhead fixed signs, changeable message signs, and toll-related structures along the median barrier.

The agreement for pavement markings involved two double-wide white stripes. The MUTCD was in the process of being changed to the recommended double white stripes found on most other buffer-separated projects that are access restricted. Due to the reduction of the left shoulder, lane width, and sight distance, mitigation included installation of reflective/yellow markers on median barriers and placement of visible/audible markers along the edge or travel way, close to the barrier where the left shoulder was 4 ft or less.

Enforcement, Maintenance, and Incident Management

CHP representatives had many options for enforcement strategies on I-110 and few options on I-10. They understood that if designated enforcement pullouts could be accommodated, it was desirable. CHP was brought in early in the development process and was a key partner with dedicated, paid representatives. Since the project was considered a demonstration with associated schedule and fixed budget, CHP was willing to settle for designs that were less than ideal. CHP was involved in enforcement plans and siting of toll readers. It has a funding

agreement with LA Metro for dedicated activities. As long as the resource fulfillment needs are addressed in operational funding (i.e., additional patrols, beacons at toll gantries, and in-vehicle toll readers), they are good partners. Several enforcement pullouts at critical points were added on I-10, and CHP can use the widened shoulders or pavement tapers at online stations to monitor traffic on I-110. The right shoulder can be used for apprehension on both projects.

Toll gantries include beacons that flash with one, two, or three colors. Each gantry site needed a CHP pull-off area so officers could observe traffic from the left but pull over violators to the right shoulder across traffic. Enforcement is present on the lanes, and the tools provided are being used. A relatively high violation rate is being observed, so enforcement remains an issue. Pay-by-plate is going well, so toll evasion is minimal. Visual occupancy detection by CHP is still problematic.

Incident management was critical for the success of both projects. While consideration was given to include incident management as part of the DBOM contractor's responsibilities, LA Metro ended up using the regional freeway service patrol contract for this function. No specific design treatments were included for incident management. The designs are considered flexible for incident management, planned events, and any emergencies.

Tolling System

Locations for tolling were determined by ease of power and straight roadway sections. Some gantry locations are on bridge structures. There are five to six toll gantries in each direction along each corridor. Typical installation involved a single gantry and pole. This approach represents a huge cost savings over prior design treatments because it can handle both cameras for license plate reads and transponder readers. A number of developers can supply this design. Most toll gantries are free standing (Figure 66). A few are located on an existing bridge. The DBOM team placed them where they were located on the preliminary layout, and if there was a structure nearby, they tried to use it.

Maintenance needs have been addressed in spaces provided. Typically, three to four cabinets are mounted near the gantry. Some cabinets are mounted on the gantry. The preliminary cabinet size was small and became bigger. Some cabinet doors are located on the wrong side and mounted 6 to 7 ft up the pole. The technologies employed leave less reason for field maintenance. The operator can perform remote access and troubleshooting of cameras, shutters, and antennas, can recycle power, etc. This practice has made a huge difference in field maintenance requirements. Technology has improved reliability without the need to go into the field as often.

If the latest approach to electronic occupancy detection proves fruitful, LA Metro would make changes to employ this approach. The industry is moving toward interoperable readers, and occupancy detection is going to be an issue that these projects have to address.

Source: Dewey

Figure 66. Typical toll gantry for Los Angeles projects.

LA Metro used existing Caltrans ITS communications capability and communications hubs while it upgraded the ITS communications capacity as part of the contract. Caltrans has an interest in sharing data (i.e., speed, volume, camera images), but progress has been slow since project opening. Co-location of express lane monitoring currently being facilitated at LA Metro into the regional traffic operation center would have been desirable. There is an ultimate need to co-locate project surveillance into the operation center, but time constraints would not allow this. Planning for I-110 project enhancements funded by toll revenues is currently underway. Issues include improving operational characteristics and safety by adding additional features, such as signs, more toll gantries for better enforcement, and partial restriping of the express lanes.

Lessons Learned

- **Partnering and resource sharing.** Stakeholder resource sharing and coordination—the team approach—is critical to an overall successful outcome. Leverage agency partner capabilities (technical, legal, and political). Identify each agency's current legal authority. A number of LA Metro staff were from Caltrans and helped foster respect among the agencies when friction occurred. Gaining new perspectives also helped see the problem from another agency's viewpoint. Agency champions supported by technical staff with responsibility and authority are needed. Partnership building is important at all agency levels.
- **First steps.** The earlier the business decisions get made, the better. The design should not be in flux late in the process. Business rules reflected in the ConOps need to be

set going in. Otherwise, the project will suffer delay and cost overruns. Establish agreements (joint use/cooperative agreements, maintenance agreements, tolling agreements, etc.) as early as possible.

- **Tolling and enforcement systems.** The tolling infrastructure should have been more expansive and comprehensive to address violators and evaders. Too many vehicles cross the buffer to enter the express lanes because of the lack of adequate toll coverage.
- **Goals.** Decision makers should define the goals of the project and the problems to be solved, and get buy-in from the disciplines and reviewers involved up front.
- **Minimizing impacts.** For conversions and first toll projects in a region, the mantra should be "no losers," at least initially. This was the county's first HOT lane project, so the degree of change was minimized to reflect user sensitivity. Environmental justice issues will always be important when tolling is a management strategy.
- **Outreach.** Engagement with key stakeholders (i.e., those who can make or break the project) is needed early and often throughout project development.
- **Project delivery.** Decision makers should consider alternate delivery such as DBOM arrangements to share or shed risk when such concerns as schedule are paramount. Consider incentive programs like LA Metro's contracting tools, which helped ensure improved delivery.
- **A systems approach.** The project should consider opportunities to link other transportation alternatives and improvements rather than just the implementing toll lanes. Try to address all affected modes. Manage the system; in other words, do not consider freeway, toll lanes, and arterials as separate systems. Managing the system to benefit the combined customer base needs more attention. Right now, express lane management is not as integrated as it should be with other initiatives.
- **Monitoring and adjusting to optimize performance.** Operational strategies should apply flexibility to change/modify operations to maximize use. The express lanes may have lost as much as 50 percent of their prior volume during the off-peak and weekend periods, which can be regained by close attention to available operation tools.

SAN DIEGO REGION

Background

San Diego is one of the first regions to demonstrate electronic toll collection on a managed lane. The region is also one of the premiere examples of integrating transit facilities into priced managed lanes as part of the same design, so for this reason, this project is included as a representative case study to highlight transit design decision-making. Caltrans has operated a reversible HOV roadway on I-15 extending from the SR 163 interchange to SR 56 (Ted Williams Parkway) since the mid-1980s. After opening, this 8-mi project provided two reversible, barrier-separated lanes to carpools carrying two or more persons per vehicle (Figure 67). The project contained high-speed flyover ramps on both termini with the freeway mainlanes and intersecting routes. However, its level of use reflected unused capacity.

Source: Fuhs

Figure 67. Original I-15 reversible HOV lanes in San Diego.

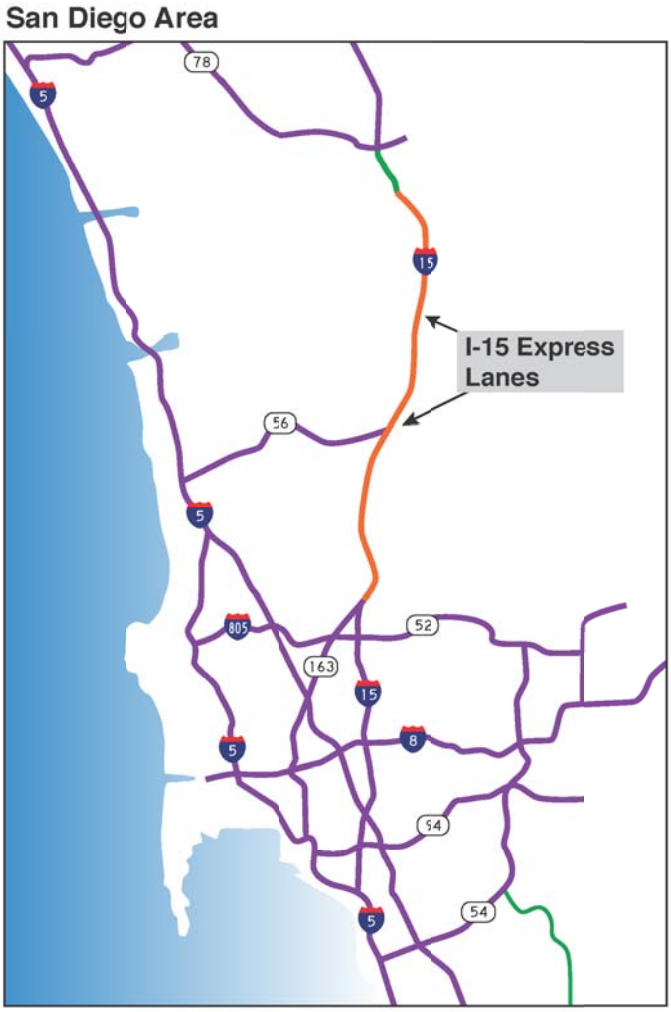
In 1998, Caltrans and SANDAG allowed single-occupant vehicles to use the lanes through a permit decal and monthly fee. This interim form of flat-fee pricing was a prelude to subsequent adoption and implementation of a dynamic tolling system employing electronic transponders. I-15 became one of the first toll applications on managed lanes in the United States. Parallel to this effort, a major investment study was undertaken that led to adoption of a multimodal solution to make the existing project better suited to BRT operation as the preferred transit mode. Light rail transit was also considered in the 1990s for this corridor, but ultimately BRT was recommended. Extension of the original 8-mi project involving multimodal managed lanes was a better solution given the travel and land use patterns of the corridor. Creating new travel choices for the corridor (BRT, carpool, vanpool, and congestion pricing) was favored by local agencies based on public input. Finding funding and obtaining Caltrans support were critical to envisioning this project since it would involve reconstruction of the freeway.

Agency and Project Context

Caltrans and SANDAG were the project sponsors to implement the study's recommendations. Caltrans was the lead agency. SANDAG and two regional transit agencies were partners who worked closely in making sure the transit service needs were being reflected in the design. All agencies were involved in creating a design concept that met the varied needs of each agency and customers in facilitating alternative mode usage.

The current completed and expanded project extends 20 mi and was reconstructed to provide four barrier-separated managed lanes in the median that could operate in either a 2-2 or 3-1

reversible configuration with a center moveable barrier (Figure 68). The expanded I-15 Express Lanes, partially funded by a local Transnet half-cent sales tax approved by public vote, was completed in three stages at a cost of approximately $1.5 billion. The first stage constructed was the middle segment, which was opened in two phases: SR 56 to Rancho Bernardo Road in 2001, then Rancho Bernardo Road to Centre City Parkway in 2009. The north segment was opened in 2012, and the south segment opened in 2011. The I-15 Express Lanes currently extends between SR 163 and SR 78, relieving congestion along the corridor. It is recognized for its innovative design and ability to provide bus rapid transit service and direct access with park-and-ride lots and transit stations located next to the freeway. It is the first segment of a regional system of interconnected express lanes. There are 20 access points. The project is available for use 24 hours a day. Carpools, vanpools, buses, motorcycles, and some clean-air vehicles are permitted to use the express lanes without a toll. Single-occupant drivers pay a toll using a windshield-mounted transponder and active account. SANDAG is the toll authority for the I-15 Express Lanes.



Source: TTI

Figure 68. Location of I-15 Express Lanes in San Diego.

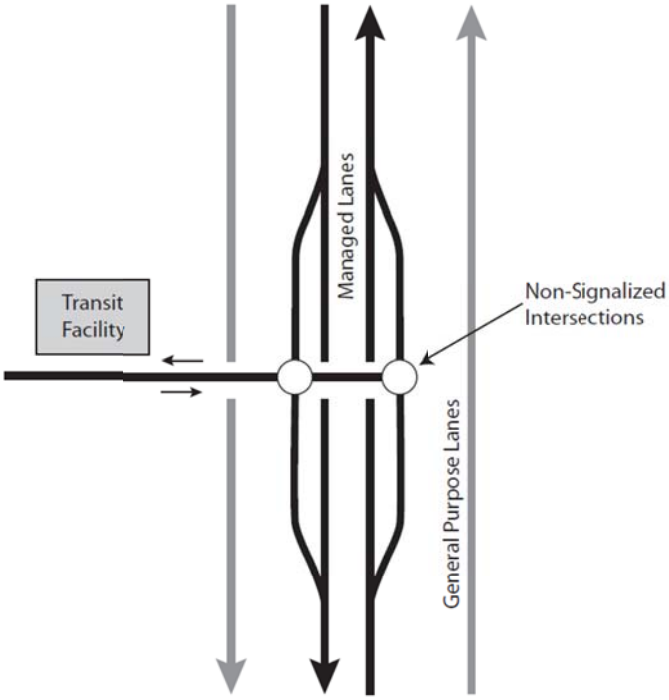
Design

Accommodating the new four-lane project design required additional right of way. For this reason, full design standards were applied to lane and shoulder widths. Outside shoulders are 10-ft wide, and the rightmost lane width is 12 ft. In order to make the moveable barrier fit a variety of operational schemes, the inside lanes in each direction are 14 ft. All ramps are on the respective right-hand side, as Figure 69 and Figure 70 show.

Fitting the transit stations and park-and-ride lots into the built community required close dialog to reach mutually agreeable solutions with local community leaders. The transit support facilities were located close enough to the freeway to provide direct-access ramps, or drop ramps with low-volume tee intersections, as shown in Figure 69 and Figure 70. Such intersections only required stop signs to handle these anticipated volumes. This design was the most reasonable in providing for a fast bus dwell time within the station while fitting within the surrounding land use.

Source: SANDAG

Figure 69. Express lane direct-access ramp to transit infrastructure prior to opening.



Source: TTI

Figure 70. Sketch of express lane direct-access ramp to transit infrastructure prior to opening.

Transit facilities were located off-line in order to be integrated as much as possible into adjacent land uses to attract demand. The freeway median was also an uninviting and noisy location from which to place transit infrastructure (SANDAG is examining online transit infrastructure in other corridors). Off-line facilities had to serve both transit and other traffic (i.e., single-occupant autos entering and exiting the express lanes, carpools, and vanpools) with sufficient space for freeway BRT service, local feeder circulation buses, and park-and-ride functions.

BRT service is branded as rapid and designed as a freeway-based service providing high-speed, limited stop service with 4- to 5-mi spacing for long-distance regional trip making. Service is segregated into two types. The first type is all-day, all-stop rapid service, which operates seven days a week on 15-minute headways. The second type is rapid express point-to-point service, which operates at 10- to 15-minute headways. Branded rapid articulated vehicles that are dedicated to the regional rapid system are used and involve several key lines regionally. Changes in service are easy to accommodate within the design with likelihood of greater bus service frequencies in the future.

The north corridor portion of I-15 is now complete. SANDAG was working with Caltrans in 2015 to add transit stations on the southern part of the corridor, which will include one section of 3-mi transit-only operation in the freeway median with online stations. Two other freeway rapid projects are planned along other freeway corridors, with one planned to open in 2017.

Unique Design Applications

The adopted concept has many unique design applications not found on other similar projects. These include broad conceptual approaches to flexibly adapt to changing demand conditions over a long design life, such as a moveable center barrier that permits up to three lanes of demand during peak periods. Smaller innovations include in-pavement dynamic pavement lighting and pop-up channelizers to divert traffic at the barrier transitions. I-15 was one of the first projects to add travel time information for both general-purpose and express lanes so that drivers could make an informed decision about opting for the priced managed lanes.

Access innovations to the design included right-side ramps for all local access necessitated by the moveable barrier, and strategic placement of transit supporting infrastructure so that BRT operations could be accommodated without stops in the median.

Lessons Learned

- **BRT and express lane compatibility.** Designing and implementing a successful BRT operation is possible with transit infrastructure as part of a priced managed lane project. San Diego's solution to provide a rail-like BRT service meant all-day, high-speed express service in a corridor that previously had only local bus service. This multimodal facility design that facilitates a range of travel choices is significant, but it requires strategic partnering with agencies charged with a vested interest in these modes.
- **Agency partnering and resource sharing.** Having the right talent and authorized role-leading partnering agencies, along with a wide range of roles to address all modes, has made a big difference. SANDAG serves many of these roles regionally as the metropolitan planning organization, transit implementer/operator, tolling agency, and planner/funding agent for highway infrastructure. SANDAG's director was a former Caltrans San Diego District director, so the knowledge and respect of agency affiliations has cross-pollinated, including technical staff as project champions.
- **Design flexibility.** The design has performed well for BRT services and can handle a wide range of different operation scenarios if required in the future. A few changes in design within the stations and ramps have been made to address bus turn radii.

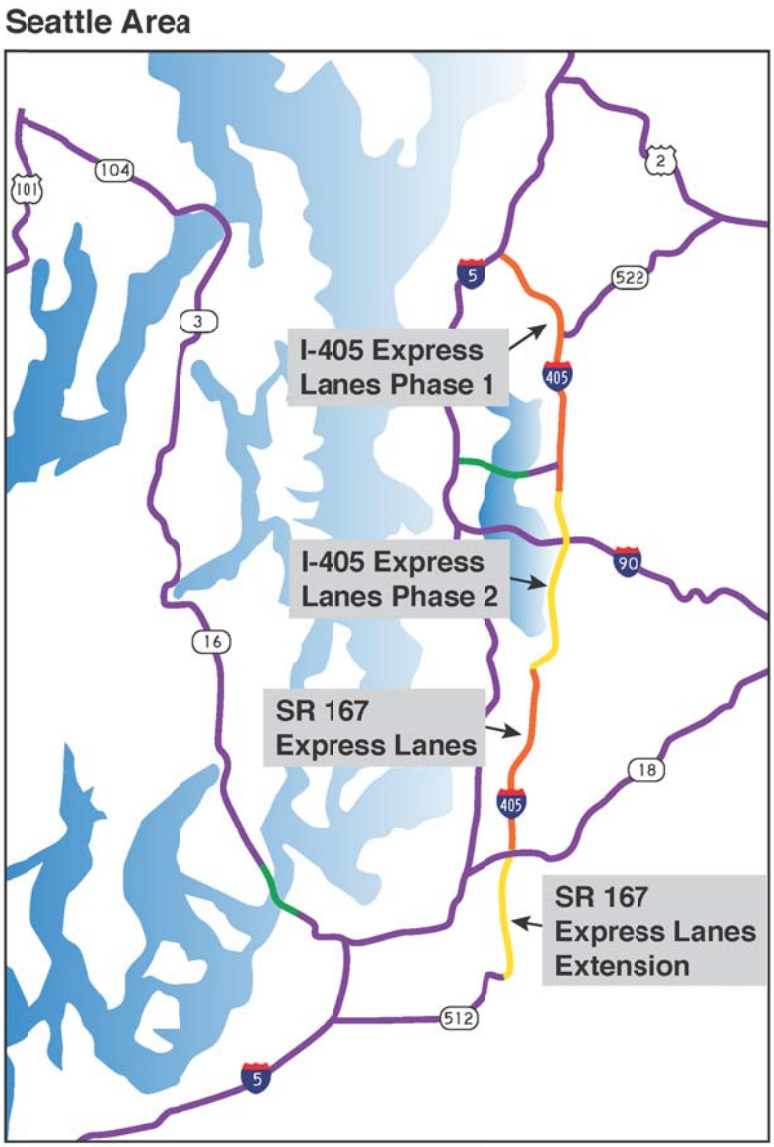
SEATTLE REGION

Background

Seattle was one of the first regions in the United States to introduce HOV lanes in the 1970s. They have designed both barrier-separated, reversible lanes on I-5 and I-90 and concurrent, contiguous HOV lanes on many other freeways in the region since then. Investments form an HOV lane system reflecting a regional plan dating from the 1990s. Seattle developed a regional policy that has been frequently updated. WSDOT has been the primary sponsor of these projects and the more recently implemented express lanes. WSDOT has a distant history from decades earlier in toll facilities on the Tacoma Narrows Bridge and SR 520 Evergreen Point floating bridge. Now, both new replacements are being tolled again. Within the past

decade, state legislation has allowed tolling on major infrastructure (bridges, tunnels, and managed lanes) in the Puget Sound region.

SR 167 and I-405 are the first two tolled managed lane projects for the region. SR 167 is a converted HOV lane that is operational, and I-405 is being developed as a new construction project that also consumes the existing HOV lane to provide two priced managed lanes. Both case studies are addressed in this section, with locations highlighted in Figure 71.



Source: TTI

Figure 71. Express lane projects in greater Seattle area.

SR 167 Express Lanes Project

Agency and Project Context

The concept for this project grew out of witnessing the initial successes of other early HOT lanes on the I-15 and SR 91 corridors in California. The SR 167 HOT lanes concept was sponsored by WSDOT in close coordination with the Washington State Transportation Commission, which had an oversight role for the agency. SR 167 HOV lanes were the first to receive tolling as a conversion demonstration due to the project's low level of use in a congested corridor. The project was implemented using dynamic pricing to actively manage demand. Specific objectives included successfully demonstrating dynamic priced tolling and maximizing performance on an underused HOV lane. The project opened in May 2008 and was the state's first HOT lane allowing solo drivers to use the carpool lane by paying an electronic variable toll. HOVs with two or more persons along with motorcycles were allowed free use. No design parameters on the HOV lane were substantially changed except for the addition of tolling, new signing and striping, and restrictions on access.

Success of this demonstration has since led WSDOT to extend the southbound direction by widening the existing roadway. Since the extension represents new construction, WSDOT is not as constricted in abiding by the same design limitations and parameters of the converted project. The extension will generally achieve full desired design standards.

Challenges included political acceptance and support as well as final facility selection since several other corridors were closely evaluated before deciding on SR 167. The project provided opportunities to test dynamic tolling and expand upon recent commencement of success in applying electronic tolling on the Tacoma Narrows Bridge.

The SR 167 HOT lane demonstration project was funded by both FHWA grants under the value pricing program and a state gas tax as part of the statewide capital improvement program. Toll authorization was provided through a pilot project by the Washington State Legislature. Federal funding availability spurred matching funding by the legislature. The project was assigned a pilot status allowing lawmakers to take a trial approach to the state's first HOT lane project. Due to limitations on how much capacity could be tolled, there was never an expectation that it could generate sufficient revenue to recover implementation costs. Rather, project revenue was intended to cover ongoing operational costs.

The launch of the SR 167 HOT lanes was an interdisciplinary effort involving civil design, traffic, information technology, planning, and construction services. At the time, the WSDOT Toll Division had not yet been created, so oversight was handled by the WSDOT Urban Corridors Office through what came to be a virtual toll organization among the different disciplines. Both regional and statewide level offices were influential in approvals needed for design deviations for shoulder and lane width, illumination design, sign spacing design, sign structure and toll gantry design, and overall channelization. Table 93 presents the geometric design parameters used in design of the roadway improvements.

Table 93. Mainline design parameters for SR 167.

Design Element	Design Standard	Existing/Proposed
Access Control	Limited Access	Limited Access
Vertical Clearance (bridges not a part of the project)	16.5 ft	n/a/16.5 ft
Bicycle/Pedestrian	n/a	n/a
Right-of-Way Width	n/a	n/a
Median		
Median Width	22 ft	Varies: 44–56 ft./44–56 ft
Median Width Transitions	60:1	100:1/100:1
Median Accident/Barrier Warrant	n/a	n/a
Median Width/Barrier Placement	n/a	n/a
Median Crossover Design	n/a	n/a
Roadway		
Lane Width	12 ft	11 ft/12 ft
Turning Roadway Width	12 ft	11 ft/12 ft
Lane Transition	60:1	n/a/70:1
Max. Superelevation	n/a	n/a
Superelevation Transition/Runoff	n/a	n/a
Lane Cross Slope	n/a	n/a
Shoulders		
Shoulder Width—Inside	10 ft	Varies: 4–12 ft/4–12 ft
Shoulder Width—Outside	10 ft	Varies: 6–12 ft/6–12 ft
Shoulder Cross Slope	2% to 6%	n/a

Source: WSDOT Toll Division.

WSDOT found that a design-bid-build approach worked well for civil construction on a project of this scale, and it used a DBOM approach for operating and tolling systems and related communication. Initially, WSDOT faced some restrictions on how it could contract these services, particularly for a DBOM procurement.

Overall Design and Operation

Design goals focused on keeping the converted facility within the existing roadway footprint and implementing a safe operating facility. Operational goals included providing a reliable trip for transit and carpools and a faster trip for toll-paying solo drivers. The parameter supporting these goals was to maintain travel speeds of 45 mph 90 percent of the time in the HOT lanes. The conversion attempted to limit changes to the geometrics of the roadway. The civil infrastructure requirements to support these goals and objectives were unique to WSDOT. A learning process has occurred since this first conversion. Related design now includes striping, signing, tolling and ITS components, additional illumination, and minor safety improvements.

The SR 167 project extension will represent a new construction widening project, and full design treatment can be fit within the available right of way. This widened roadway section will exhibit full 12-ft lanes, a 10-ft inside shoulder (14 ft in some sections based on enforcement needs), and a 2-ft buffer.

Separation Buffers and Shoulders

Based on the need to minimize reconstruction of outside shoulders, the typical section for the original SR 167 conversion that allowed the HOT lane, buffer, and shoulder along with two GP lanes to be accommodated within the available 35- or 36-ft travelway was developed. This section is shown in Figure 72 and Figure 73 and included:

- 4-ft to 10-ft inside shoulder (based on available width).
- 11-ft HOT lane.
- 2-ft buffer.
- 11-ft leftmost general-purpose lane.
- 11-ft to 12-ft outside general-purpose lane (based on available width).
- 6-ft to 12-ft outside shoulder (based on available width).

Source: Fuhs

Figure 72. Typical separation marking before conversion.

Source: Fuhs

Figure 73. Typical separation marking after conversion.

WSDOT design standards were not met in two areas—maintaining 10 ft for both inside and outside shoulders and maintaining a 12-ft lane width. Deviations were needed to reduce the lane and shoulder widths in some areas, due to the need to remain within the travelway. In many cases, these deviations were exacerbated by the addition of widened median barrier foundations for toll and sign structures. An example condition is shown in Figure 74.

Trade-offs were treated in the following manner within the constraints of the overall width. First, the width of the HOT lane was reduced to 11 ft along with the outside general-purpose lane in some sections, based on the need to maintain a 2-ft buffer. Next, both inside and outside shoulder widths were reduced. Shoulder width was reduced in areas where additional median barrier width was necessary to accommodate widened barrier foundations for toll gantries and sign structures. This hierarchy in making trade-offs has worked well in an operational setting in which no safety concerns resulted. In several areas, roadway width was further constrained at existing bridges. Where such structures interfered with sign spacing or toll point spacing needs, equipment and signing were installed from the bridge median barrier, reducing the need for gantries or sign structures.

Hydraulic and hydrologic analysis for the project was limited due to the following considerations:

- A conversion project added almost no new or replaced impervious surface. Work was limited to small footings and foundations for illuminated signs and striping since work fell below the 2000 sq-ft new and replaced impervious surface threshold requiring storm water control measures.

- Trench drains were constructed in some shoulder superelevation locations as a maintenance change to fix existing ponding problems on the roadway. The locations for the trench drains were based on observations by maintenance personnel and limitations on the amount of trench that could be constructed.

Source: Fuhs

Figure 74. Local design deviation on inside shoulder.

Access

The previous existing design includes a left-side lane restricted to HOVs separated from adjacent traffic by a wide white stripe. The HOV lane could be accessed anywhere. Restricting access was felt critical to managing a tolled lane. Five northbound weave zones and three southbound weave zones were created in a restricted-access setting. Each zone involved a change in the pavement striping and signing to allow simultaneous entry and exit. Safety concerns were raised about the locations and characteristics of restricting access to designated points, especially in regards to locating these in relationship to mainline right-side exits and entrances. Lane weave distances as well as information gathered from the I-394 project in Minneapolis were considered in the final design. WSDOT attempted to provide 1000 ft per-lane weave in locating access zones. During the first weeks of operation, access zones were lengthened to provide a more efficient means for ingress/egress based on buffer-crossing observations. Some guide signs were added to median barriers, so customers were better informed about where to enter and exit the lane.

The entrance to the HOT lanes was not altered from the prior HOV design. In the northbound direction, the roadway widens for an HOT lane and is marked with wide dashed lines; it turns into a general-purpose lane near the terminus of the highway. In the southbound direction, a

left general-purpose lane changes to an HOT lane with signing and two dashed stripes; it ends by becoming a third general-purpose lane with the right lane dropping to a downstream exit ramp.

Once HOT operations began, drivers often violated the access restrictions and entered prior to the opening. In August 2014, WSDOT was awarded a federal grant to change the access back to the prior HOV open-access design. Some signing was removed or modified in conjunction with restriping the project. Access restrictions were retained in high-volume areas near the project termini. WSDOT is now monitoring the results of this change. In retrospect, WSDOT might have taken a different approach to access design, and monitoring results will confirm what is learned. Prior HOV motorists who were used to accessing the lane at any point may have played a role in a push-back from customers after the restriction was enacted.

Signing and Pavement Markings

Conversion involved restriping and re-signing the roadway to post pricing information, regulations for users, and access zones. The most critical needs were for posting toll rates, entrance/exit locations, and signing to enforce buffer crossing. HOV signs were removed. Prior to the access changes, the typical sequence involved an advance access sign a half mile upstream, followed by a toll rate sign, both of which were mounted over the HOT lane. On this demonstration, customers see only one toll rate, which is effective for the entire distance. Posting toll rates was considered a priority in the signing hierarchy, except when other messages addressing an operational condition where the lanes cannot be priced or used are displayed.

Pavement markings for the buffer consisted of two 8-inch-wide solid stripes in restricted-access segments, with an 8-inch middle gap, yielding a total buffer of 2 ft. Other separation designs were considered but ultimately not selected based on limitations on the available roadway width and success seen on other similar facilities, notably I-35W in Minneapolis. WSDOT is comfortable with a 2-ft buffer for a single-lane facility, but it will continue to monitor and evaluate operations. Future projects may consider no buffer or a virtual buffer. The design-build contract for the southbound SR 167 extension has been awarded, and it will apply continuous access and provide for a buffer width if required in the future. This approach gives WSDOT design flexibility.

Enforcement, Maintenance, and Incident Management

The Washington State Patrol (WSP) has been a long-time, close partner of WSDOT in providing managed lane enforcement. No new enforcement areas were created as part of the conversion project, and few areas exist to turn around. Enforcement of the SR 167 HOT lanes is conducted by WSP, and representatives were included in some of the initial planning and design efforts. No specific enforcement design was adopted, so WSP involvement was focused more on the toll system enforcement applications including a field beacon at a toll gantry. Enforcement monitoring was considered in two venues—the toll system side as well as the roadway side. With the limited roadway cross-section available in many locations of the facility, some roadway design improvements to support enforcement and incident

management were not included because they were outside of the scope and funding of the civil engineering construction efforts. Enforcement beacons were installed at each toll gantry to alert enforcement officers when paying customers traverse the facility. Enforcement operations have been performed around areas where wide shoulders existed in the alignment. No enforcement design changes are planned as part of the current SR 167 HOT lanes project. However, looking at future HOT lane facilities in the region, wide inside shoulders downstream of toll points are being planned. For the southbound extension, WSP has indicated that it would prefer a longer 10-ft shoulder versus a shorter 14-ft enforcement shoulder so that officers can have longer areas in which to pull violators.

No major maintenance issues were identified in designing the project. Snow removal was only peripherally considered. The profiled striping in the buffer has been worn down in part by snow plow activity. Drainage and ponding was only considered in a few areas as part of roadway maintenance improvements.

Tolling System

Based on the project ConOps, the project was initially envisioned as a tag-based application to test interest in tolling. Federal conditions shifted this approach to full testing of electronic toll collection via transponders. Specific toll infrastructure was heavily influenced by input from WSDOT's toll vendor at the time. Access restrictions on the SR 167 project were based on this input. The toll system performance requirements arising out of the ConOps led WSDOT's toll vendor to include additional requirements for toll equipment infrastructure. For example, WSDOT's performance requirement for AVI accuracy and avoidance of cross-lane tag reads caused the vendor to install a guard antenna over the leftmost general-purpose lane, thereby requiring that the toll gantry structures extend over both the HOT and GP lanes.

Toll gantries were located based on the initial access points. The toll system mounting was designed based on the technical solution proposed by WSDOT's toll vendor in meeting the performance requirements of the tolling system. In most cases, the overhead antennas are mounted onto signal mast arms with a bracket. Most tolling equipment is placed on independent structures. Two locations exist where toll equipment was installed on either a bridge overpass or an existing sign bridge. Evaluation for the existing structures was provided through the state bridge office in coordination with the toll vendor design. Given the evolution of tolling in Washington State since the HOT lanes opened, many changes would be made to the initial design. However, at the time, design practice was in line with the state of the practice before a system-wide need was evident.

Lessons Learned

- **Planning for success.** Transitioning the SR 167 project from pilot status to a permanent facility has limited WSDOT's ability to program future improvements. Having a firm exit strategy from pilot status, in hindsight, would have been helpful.
- **Design parameters.** The original conversion required a limited scope and budget, which drove some of the design process and outcomes. If WSDOT were to take on a similar project now with an HOT lane that would operate in perpetuity, staff might

look at things like making the roadway wider or providing better shoulders. They were forced to take a shorter-term view on the SR 167 demonstration to avoid environmental issues and cost, not knowing the longevity of the proposed concept. Looking forward, both conversions and new capacity comprise the region's express lane plan.

- **Project scope.** SR 167 was treated as an operational improvement using an approach led by WSDOT's operations group to analyze impacts and manage the degree of design modification to be made commensurate with the design investment and operation life of the pilot. A design matrix needs to be established for highway projects to spell out what requirements should be met for a tolled managed lane. Region traffic staff and what came to be the toll division staff understood that the SR 167 conversion was not a standard roadway project. WSDOT technical staff had to make allowances for that paradigm shift. "Practical design" has become the new mantra within WSDOT. Its tolerance for what is acceptable is increasing as a result of the SR 167 experience. The new southbound extension will represent a capacity improvement, so assumptions related to design trade-offs will change from what will fit within the existing pavement footprint to what can be provided within the available right of way.
- **Embracing changing technology.** The short life cycle of tolling infrastructure and speed associated with technology advancements have made it difficult to develop standards of practice, and this matter is exacerbated by what was a lack of appreciation that pilot projects could become part of an adopted tolled managed lane system.
- **Performance monitoring.** WSDOT has been particularly adept at documenting lessons learned from its demonstration projects. A wide range of process and outcome-oriented experiences by functional discipline are available in a report entitled *SR 167 HOT Lanes Pilot Project Lessons Learned: Getting to Opening* (*226*).

I-405 Corridor Express Lanes Project

Agency and Project Context

WSDOT is planning a second major express lane project in the I-405 corridor. The project has been in development for about a decade. Originally, concurrent HOV lanes were designated in the right-side shoulders of I-405 to help transit buses reach interchanges where park-and-ride lots were located. This design created increasing conflict with on- and off-ramps as traffic volumes increased. The HOV lanes were eventually made more permanent by restriping the roadway and relocating them next to the median barrier. Grade-separated median drop ramps were added at major locations where transit stations were located. The existing HOV lanes perform poorly and are classified by WSDOT as degraded. Raising the minimum occupancy requirement to HOV 3+ was considered, but results showed that operating two express lanes would result in greater person and vehicle throughput.

This project will involve new construction to expand the single, concurrent HOV lanes to dual buffer-separated express lanes with designated access points. The 17-mi first-phase project is being constructed and is scheduled to open in late 2015. A second-phase between Renton and

Bellevue will connect this segment to the existing SR 167 HOT lanes and is unfunded. The Renton segment calls for two express lanes plus one general-purpose lane, so widening will be costly. For this reason, WSDOT is examining an interim project that may toll the existing HOV lanes in this segment.

Limits for these phases were established based on available funding and consensus among local elected officials and the state legislature. By narrowing lanes and shoulder widths to reduce structural impacts, the limits of the initial phase were extended by approximately 1 mi from SR 520 to NE 6th St. The balance of I-405 topics covered below are specific to the Bellevue to Lynnwood project in construction and based on a corridor analysis (*227*). The design of the Renton to Bellevue portion is preliminary and subject to change.

Similar to SR 167, the I-405 Express Lanes will use dynamic pricing to actively manage traffic. Reducing congestion, increasing transit speed and reliability, and providing travelers with a choice for a faster, reliable trip are goals and anticipated benefits. Launching the project will allow WSDOT to continue offering reliable trips, actively manage demand, and help augment funding for future improvements in the corridor. Funding will be provided as part of a statewide capital improvement program. Toll authorization for the facility in a pilot status was authorized by the legislature. In the authorizing legislation, broad performance measures were outlined for the project between Bellevue and Lynnwood.

Initial coordination within WSDOT and FHWA has focused on how to design lane separation and access since no guidance exists in the WSDOT *Design Manual* (*29*). Looking at FHWA guidance, Caltrans guidance, and other available data, designers prepared a corridor analysis to document how the express toll lanes would be designed. Working through the project scoping and preliminary design process included an extensive effort to build consensus among elected officials and the public. Maintaining support and confirming early design and funding/financing decisions were challenges to overcome. This process included an expert review panel focused on reviewing modeling and financial assumptions. An independent evaluation of traffic and revenue forecasts was also completed. With these independent checks on WSDOT studies, consensus among stakeholders was reached to move forward with construction of the first phase.

Project Delivery

The express lanes will require additional elements, such as toll gantries and segregated toll and ITS fiber communications networks, which are not included in a standard highway project. Specifications for those elements were required and were written to be procured through a design-build contract. These specifications had to be prepared prior to a regional toll vendor being chosen, so terms were intentionally broad to account for many possible toll solutions. Final details were then adjusted after construction contracts had been awarded. Having a separate toll vendor contractor to coordinate schedules and design details also differentiates this project.

Full funding to construct the express lanes was provided as part of a statewide capital improvement program, which allowed WSDOT to follow more traditional procurement

options rather than consider innovative financing or other partnership approaches. The first-phase project is being delivered with two contracts—one for the civil widening and one for the toll system. The civil portion including roadway design, drainage, and toll infrastructure (gantries, cabinets, ITS fiber) is a DB contract. The civil portion is responsible for the final design of the roadway widening and for specific pieces of infrastructure needed for the toll system, plus overall quality control. WSDOT administers the contract including design review. The roadway design guidance was established in a corridor analysis approved by FHWA that the civil engineering DB developer was required to follow, or obtain a deviation if it could not meet it. This DB contract included both the corridor analysis and preapproved design deviations from the WSDOT *Design Manual*. These documents provided the available envelope that the DB team had to work within for the roadway design. The procurement documents provided the specifications for other disciplines. The civil DB contract includes specifications for many aspects that the project had to be designed within, including the corridor analysis defining the express lane design and access points. Additional specifications in the procurement related to items the civil DB provided for the toll vendor such as the toll gantries. The civil DB was responsible for the final design of all elements, including locating the access points, toll gantries, and signing.

The toll vendor procurement was awarded in 2012 for tolling equipment (readers, antennas, etc.), software, and ongoing maintenance and is a DBOM contract. This agreement holds the vendor responsible for system maintenance and performance after opening and on other tolled routes for nine years past the toll commencement date for the last facility. The toll vendor contract provided the parameters for the infrastructure that the civil engineering design-builder would provide. If modifications were needed, WSDOT worked with both contractors to determine if the modifications could be accommodated and how to account for any cost increase. The toll vendor was required to perform quality control for its activities, but state policy requires an independent quality assurance firm under a separate agreement to be involved and overseen by WSDOT. Each contract was as prescriptive as possible regarding areas where work either overlapped or touched, while more latitude was given in other areas where less overlap was apparent.

Providing a clear demarcation point between the two contracts was a challenge that WSDOT worked through in preparing the two procurement documents. The scope of each contract was chosen based on which contractor would have the best expertise for design and procurement. Once the civil design-builder had installed and tested toll infrastructure, the project was turned over to the toll vendor. At that point, the civil engineering design-builder no longer had access, reducing the likelihood of one contractor interfering with the work of the other.

Design

Early coordination between WSDOT and FHWA about the roadway widening constraints and express lane design helped to keep the project moving through the initial roadway design and documentation. Having agreement on these aspects smoothed the environmental permitting effort by limiting changes to the project footprint later in the permitting process.

The environmental assessment (EA) for the project looked at two operational scenarios—express toll lanes and a combination of HOV/GP lanes. The EA concluded that express lanes would move more people and vehicles. Express toll lanes with buffer separation and designated access points were the chosen solution. At each access point, the design type was chosen within the parameters established in the corridor analysis. Existing right of way, environmentally sensitive areas, and bridge structures limited ability to widen I-405 through the entire corridor. These constraints resulted in narrowed lane, shoulder, and buffer widths in places. No structure replacements were planned because WSDOT was trying to avoid replacing structures due to cost and traffic impacts. Minimizing rebuilding of structures allowed for the funded project limits to be extended an additional mile. The NE 6th Street direct-access ramps were determined to be logical interim termini for the south end of the project, with left-side drop ramps providing access into and out of downtown Bellevue.

A desirable cross-section will be 10-ft shoulders, 12-ft lanes, and a 4-ft buffer between the express and GP lanes. This section cannot always be achieved. The minimum cross-section will be 2-ft shoulders, 11-ft lanes, and a 2-ft buffer. The express lane system and the varying number of lanes will mean that there is no typical section. A hierarchy for cross-sectional trade-offs was established for this project, initially involving the left (inside) shoulder next to the median barrier, and then buffer and then lane widths. WSDOT's hierarchy is documented in the Design Deviation #1 Roadway Section approved by FHWA and referenced below (*6*):

> The first priority is to maintain standard shoulders, on both the outside for a refuge area, and the inside for refuge and enforcement. Shoulder widths between four and eight ft are not desirable (WSDOT DM page 1140-9, July 2011). Inside shoulder widths less than four ft can result in negative impacts to drainage, lighting, ITS items and sight distance. After shoulders, the priority is a four-ft buffer, with a minimum buffer width of two ft to allow enough separation to clearly show two wide white lines. After buffers, the priority is lane widths. Location for standard width lanes is chosen depending on the elements that are deviated. For example, if there is available width to only have one 12-ft lane, and there is a narrow inside shoulder, the 12-ft lane will be the express toll lane next to the narrow shoulder.

Discussion about the desirable cross-section focused on the width of the buffer because that was the only element not specified in the WSDOT *Design Manual*. Buffer widths for the I-405 project are measured from center to center for the two stripes, similar to how lane widths are measured. (In comparison, the SR 167 buffer width is measured from the outside of each stripe, and it has a 2-ft buffer.) However, available national design guidance suggests that a 4-ft buffer is desirable. Therefore, the I-405 corridor analysis specifies a 4-ft buffer, and a design deviation is required where that width cannot be provided.

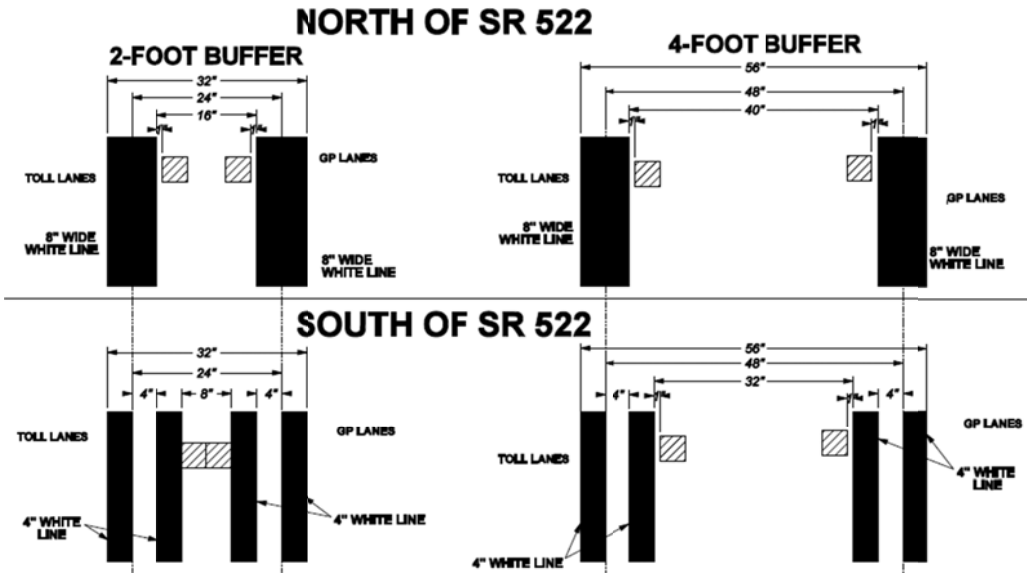
Many existing bridge structures within the corridor will not be modified by the project. Additionally, many new sign structures, toll gantries, and luminaires will be installed with foundations that are wider than the standard median barrier. In areas where the structures or foundations will reduce the available roadway width, a design deviation was prepared to document the location, reduced width, and reason for the reduction and was approved internally and by FHWA.

Narrow shoulders will reduce the available horizontal stopping sight distance (HSSD) around a few curves. These deficiencies were corrected to the extent possible by maintaining a wide shoulder in those areas. Where HSSD could not be provided to meet the design speed of the project, a design variance was obtained. Median shoulders will be provided for refuge and enforcement wherever sufficient roadway width is available. Median shoulder widths will range from 2 ft to 10 ft within the project area. An 8-ft width will provide refuge for disabled vehicles, while 10 ft is required for enforcement activities. Approximately 45 percent of the project will have an inside shoulder that is 10-ft wide.

The biggest drainage challenge resulted from areas where existing shoulders will be narrowed to accommodate the additional lane or buffer. In these areas, additional design and construction will be needed to ensure that the flooded width does not encroach into the travel way. Additional drainage catch basins and other measures were installed to prevent any adverse impacts.

Separation Treatment

A painted buffer will separate the express and GP lanes. This buffer will vary between 2- and 4-ft wide in segments outside of access points. Striping will consist of either two or four stripes, depending on the buffer width (see Figure 75).



Source: WSDOT I-405 corridor program, Washington State Department of Transportation

Figure 75. Striping for I-405 Express Lanes.

The current buffer design does not include pylons. Safety concerns related to motorcycles crossing the buffer led to a decision to not profile the solid buffer lines, in accordance with WSDOT policy for HOV lanes. The corridor analysis allows for active separation, such as pylons, to reduce friction between the express and GP lanes, if needed. Implementing active

separation has been deferred until after opening. However, if there appear to be operational challenges with compliance, pylons may be installed. Other options considered for active separation between the two roadways include raised pavement markers (RPMs). The use of RPMs will not be included in the final project design. WSDOT intends to monitor the operations closely after the project opens. Changes to the access point design, striping, and buffer design may be made at that time based on operational experience.

Access

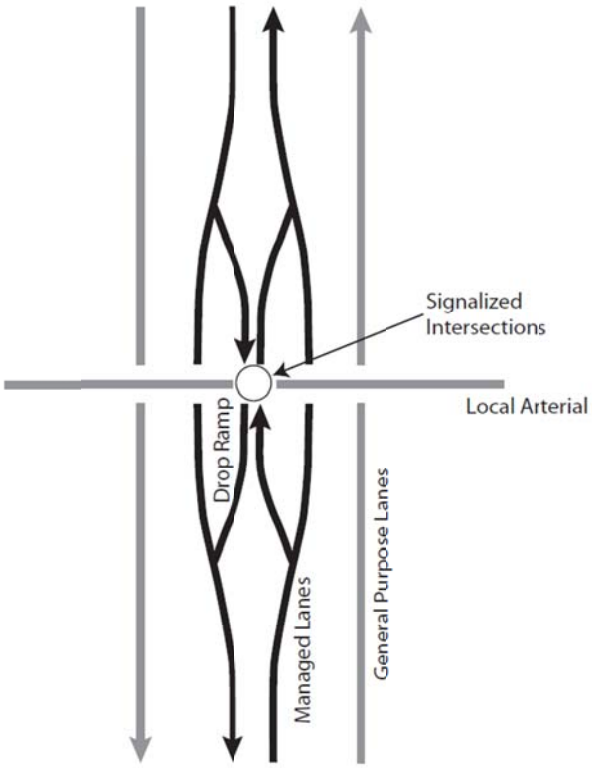
Access points will be provided where sufficient weaving distance is available to nearby right-side general-purpose ramps. The weaving distance was defined on a per-lane change-required basis, with a minimum length of 800 ft and a desirable length of 1000 ft for each lane change. This basis was supported by a review of Caltrans guidance and recent studies and operational modeling. Both shared- and single-direction at-grade access zones will be provided, as well as direct-access drop ramps where these facilities already exist. Two types of designs will be used for shared access—weave lane where an additional lane is created for the weaving between the two roadways, and weave zones where vehicles weave directly across (see Figure 1). Channelized ingress-only locations will be applied in two areas within the corridor where motorists can enter the lanes but cannot exit. The corridor analysis includes factors that influence the choice of one design type over another. For the civil engineering DB contract, the procurement specified the design type to be provided at each access point. Generally, the preference was for a separate weave lane to be included within the dual-lane system due to the expected high traffic volumes. VISSIM models were created to study the operational impacts on the design options. Access types were chosen based on the traffic characteristics and geometric constraints at each location.

Two existing direct-access drop ramps to cross streets will be included within the project (Figure 76 and Figure 77). These ramps were built for HOV and transit needs with federal and local transit funds and are proposed to be converted to allow for use by toll-paying vehicles. WSDOT is in the process of conducting negotiations between FTA and Sound Transit and has issued a request from the Washington State Secretary to FTA to open up these ramps to proposed express lane traffic. Future direct-connection ramps are planned at the I-90 and SR 520 interchanges with intersecting express lanes. The near-term project will call for a direct connection near Renton for I-405 Express Lane connectivity to SR 167 farther south. All direct-connection ramps will operate two-way.

The corridor analysis provides a schematic showing how the express lanes will begin or terminate. In the southbound direction, one lane will drop onto the left-side direct-access exit to NE 6th St. The remaining lane will continue just past the physical gore of the direct-access ramp. The buffer striping will taper from a 2-ft width to a single stripe. After allowing for weaving of SOVs leaving the project, the HOV restriction will be reinstated for the leftmost lane. In the northbound direction in Bothell, the dual express lanes will transition to a single lane. This transition will introduce a taper between the two express lanes while reducing the taper between the rightmost express lane and the GP lanes. In Lynnwood, the single express lane will continue as a general-purpose lane for all traffic approaching the I-5 interchange. The buffer will be tapered out and the lane will open to all traffic.

Source: Fuhs

Figure 76. Existing drop ramp along I-405 proposed express lanes.



Source: TTI

Figure 77. Sketch example of drop ramp along I-405 proposed express lanes.

Signing and Pavement Markings

The access points and payment methods were the two most important signing needs. A standard series of signs was developed leading to each access point, with messages for general-purpose vehicles wanting to enter and express lane traffic trying to exit to a right-side interchange. The design team was conscious of the challenge of providing sufficient information for corridor users without creating sign clutter and message overload.

Overhead signing is used for guidance and payment methods. Side-mount signs provide information on operational rules such as buffer restrictions. When approaching an access point, a series of three signs with messages for both traffic streams is provided:

- Advance Access—Approximately 0.5 mi prior to an access point, a LOCAL EXIT sign over the express lanes indicates which general-purpose exits can be reached. Over the GP lanes, signing indicates the payment methods and upcoming access on the left. Side-mounted signing, where space was available, provides the "Good to Go" phone number for setting up a transponder account.
- Toll Rate Sign—Approximately 300 ft prior to the access, a second LOCAL EXIT sign over the express lanes again indicates which general-purpose exits can be reached. Over the GP lanes, the current toll rate is posted to three downstream destinations and displays the current HOV toll-free occupancy requirement. A side-mount sign, where space was available, indicates the pay-by-mail differential that will be added to the posted toll rates for customers without a Good to Go account.
- Access Sign—Within the access, a sign over the express lanes includes down arrows pointing at the express lanes.
- After the access, mounted to the upstream toll gantry, a side-mounted sign indicates PHOTO TOLL SYSTEM IN USE, as required by the legislature.

The Phase 1 project will be divided into three toll segments with a price shown for each segment a customer might traverse. Focus groups were employed to test signing concepts. Feedback showed that customers were very interested in knowing the full price of the trip prior to entering the express lanes. As such, customers will be charged one of the rates shown, with any intermediate destinations priced to the end of that specific segment. Overhead signing will be used to provide information on access points, toll rates and occupancy requirements, and payment methods. All other information will be conveyed through side-mounted signs. Limiting overhead signing was preferred to reduce sign clutter in the project corridor and enhance the ability of users to distinguish express toll lane signing from general-purpose lane signing.

Clearly distinguishing express lane signing in the corridor was the biggest challenge in designing the signing layout. The use of an EXPRESS TOLL LANES banner across the top of all respective signs is intended to help users distinguish this project. The use of a white background on all signs is another way to distinguish them from general-purpose signage and is similar to the sign colors of the HOV system. The use of a purple banner to distinguish toll signs from general-purpose signs would have been applied if the option were available.

The federal MUTCD examples were referenced, but they do not clearly define over which lane signs should be located, nor do they specify which messages should be on the right or left of traffic. This review led WSDOT to evaluate signing design late in the project development process. Smaller side-mounted information signing about the toll system rules is also not well defined in the MUTCD.

Buffer striping designs are either two 8-inch white stripes in the single-lane section or four 4-inch white stripes in the two-lane section. These are based on the MUTCD for buffer-separated lanes. In-lane pavement markings are suggested by the MUTCD but will not be incorporated throughout the project length. Concerns about maintainability of pavement markings, especially if within the wheel path, led to this decision. Pavement markings noting EXPRESS TOLL LANE will be included within the access points only when the system opens. These markings may be allowed to wear off after users adjust to the operation. Buffer stripe options—when to use a double white line versus the double-double white line—are not clear in the MUTCD guidance.

Enforcement, Maintenance, and Incident Management

WSP input was received on the roadway design elements early in the project. Troopers identified the need for a 10-ft minimum shoulder width for enforcement located following each toll gantry. Wider shoulders in select locations would not be a preferred method of providing for enforcement. The troopers preferred a more continuous 10-ft-wide shoulder to shorter areas with a 14-ft-wide shoulder. Having longer available length provides them with more options.

WSP also provided input on the mounting location of the enforcement beacons. Coordination with WSP determined the type of on-site enforcement areas needed and led to the requirements that were included in the civil engineering DB procurement. The WSP will use the inside shoulder for on-site enforcement of occupancy, access, and other rules of the road such as speeding. The civil DB procurement required that an enforcement area meeting the WSDOT *Design Manual* requirements be provided following mainline toll gantry locations. In some instances, the toll gantry locations moved downstream in the design to an area in which sufficient shoulder width was available. At the southern end, the available shoulder widths will not accommodate an enforcement area, and roadway widening was not feasible. Toll gantries will have a beacon mounted over each toll lane to allow WSP to verify vehicle occupancy.

Typical incidents will be handled by WSP and WSDOT's incident response team. One incident response team truck is dedicated to I-405 during the peak periods and roams the area throughout the midday. These trucks reduce the effect of incidents and breakdowns, helping to clear the road faster. WSP will determine when to close the express toll lanes or to route all traffic into the lanes in the event of an emergency or incident. No special design provisions were made for these events. Even though snow plowing is rare, one consideration in the decision to delay implementing pylons was consideration of snow events.

Tolling System

Toll gantries were planned based on the access location and available shoulder width for enforcement and maintenance activities. The civil DB procurement provided the broad parameters for locating toll gantries. The selected civil DB firm then finalized the location based on additional factors such as proximity to existing electrical services, separation luminaires, and roadway signing. Toll gantries will not be located on bridges. The toll vendor determined how to mount the toll equipment to the gantries. The civil DB firm was responsible for the design and construction of the toll gantries to provide a structure that operated within vibration and deflection ranges, based on the weight and wind loading of the toll vendor's equipment.

At each toll gantry location, maintenance access for a small vehicle to pull into the median shoulder will be provided. Roadside toll cabinets at both the toll gantries and the toll rate signs will be located on the outside of the roadway and will have a maintenance pullout as well. At the foundation, a level concrete pad will be provided for maintenance personnel to stand on to access the cabinets. For median toll gantry foundations in concrete barriers, maintenance personnel will need to stand on the barrier while performing their work. At each toll point, two toll gantries spaced about 30 ft apart will be provided. Between the two foundations, the barrier width will be 4-ft wide to accommodate junction boxes, allowing sufficient width for the personnel to safely perform their duties. A width of 4 ft is also what will be needed for the toll gantry foundations, resulting in constant median barrier width within the toll zone.

Access to equipment over the lanes, including the toll equipment and toll rate signs, will require lane closures and personnel using bucket trucks. Most toll gantries will be free-standing, mono-tube cantilever structures with the foundation in the median barrier. Some toll gantries were designed along with sign structures that span the entire roadway. Toll gantries were required to meet the vibration and deflection criteria and vertical clearance requirements. Where combined with additional structures, the DB firm analyzed the structures to show that they meet the requirements.

Lessons Learned

- **First steps.**
  - Roles and responsibilities of the project team need to be established and documented as early as possible in the project development process, preferably before commencing work on the ConOps.
  - Operational policies, such as a carpool policy, should be determined as early as possible to limit later changes. Following best practices in systems engineering, the ConOps and system requirements should be fully developed and finalized before the civil engineering and system designs begin.
  - Developing the roadway design early in the process worked well. Coordination within divisions and FHWA allowed for the roadway design to be set early, minimizing the impact of any changes later in the environmental permitting process.

    - Sign concepts and design should be finalized as early in the project development process as possible. Designs and layout should be reviewed by a broad group of internal stakeholders, including management and communications, to ensure that everyone buys into the proposed design. WSDOT has subsequently developed and issued a toll sign guidance document (*228*) to provide clearer direction to future projects now that a regional system is planned.
    - After construction begins, clear demarcation between contracts will reduce claims and ease administration. Communication is key to ensuring that all groups are working toward the same goals, including conflict resolution plans covering areas of overlap.
- **Project delivery.** Toll vendor contracts should be executed prior to finalizing the civil design-build procurement. This process will allow the toll vendor or toll systems provider to review the requirements, reducing changes later in the civil design and construction processes.
- **Design specifications.** Civil engineering procurement specifications for toll-related items are different than for a standard highway project. In particular, specifications for the fiber communications network design, toll rate signs, and cabinet locations may need to be modified to support a toll system.
- **Project coordination.** The civil design procurement defined the items that were needed prior to the toll vendor beginning installation. To reduce conflicts, the ITS components should be completed in areas in which the toll vendor will work.
- **Performance monitoring.** WSDOT will continue to evolve standards of practice. The I-405 project is going to be similar to the SR 167 demonstration in that performance monitoring and regular reporting will occur, and documentation of lessons learned will be made. WSDOT will then make informed decisions regarding design changes. Keeping an active interest in operational outcomes means WSDOT is responding and attentive to that need.
- **Regional guidance and preferred practices.** A longer-term need is an official update to the WSDOT *Design Manual* that addresses express lanes. WSDOT is not holding up the I-405 project as the adopted design standard and expects to continue to improve or change design features. Not enough experiences have occurred to validate a preferred design or operation. Much was learned and applied from the SR 167 tolling demonstration.

APPENDIX F

SUGGESTED CHANGES TO REFERENCE DOCUMENTS

OVERVIEW

Potential changes to key reference documents are provided in this appendix.

AASHTO *GREEN BOOK*

AASHTO's *A Policy on Geometric Design of Highways and Streets*, commonly known as the *Green Book* (*7*), has chapters on freeways (Chapter 8) and grade separations and interchanges (Chapter 10) that contain material relevant to managed lane design. Section 8.4.8, within the freeway chapter, is on accommodation of managed lanes and transit facilities. Managed lanes are defined at the beginning of this section as "highway facilities or a set of lanes where operational strategies are implemented and managed in response to changing conditions to increase freeway efficiency, maximize capacity, managed demand, and generate revenue. Examples of managed lanes include high-occupancy vehicle lanes, value-priced lanes, high-occupancy toll (HOT) lanes, and exclusive or special-use lanes such as express lanes, bus lanes, transit lanes, and reversible flow lanes" (used by permission). Within the introductory paragraph of Section 8.4.8, the *Green Book* provides two references for additional information: a 2004 report entitled *Managed Lanes: A Cross-Cutting Study* (*53*) and the 2003 version of the FHWA *Freeway Management and Operations Handbook* (*45*). Most of Section 8.4.8 is devoted to transit, with several figures showing how to incorporate bus stops at the freeway level. There is one paragraph on exclusive HOV lanes, written within the context of bus transit. That paragraph references AASHTO's *Guide for High-Occupancy Vehicle (HOV) Facilities* (*3*) and *Guide for the Design of Park-and-Ride Facilities* (*43*). The chapter on grade separations and interchanges does not discuss ramp design for managed lanes.

Currently, the *Green Book* is comprehensive in addressing design issues, with over 800 pages. The AASHTO task force responsible for the document recognizes that the document is very large. Adding the breadth and depth of information needed to cover the issues related to managed lanes is beyond the document's capacity, and creating a unique document dedicated to managed lane design (i.e., *NCHRP Research Report 835* [*1*]) is in line with the goals of the AASHTO task force. Therefore, the recommended changes to the *Green Book* from this project are intended more for reference than large-scale revision.

Based on the results from NCHRP 15-49, it is recommended that a one-paragraph subsection entitled "Passenger Vehicles" be inserted into Section 8.4.8 between the existing subsections entitled "General Considerations" and "Buses." The paragraph in that section would contain text similar to the following:

> Freeway managed lanes can be used for many purposes and can be implemented in a variety of ways to move personal automobiles and other passenger vehicles from one

> place to another on the freeway. Because there are so many variations of managed lane facilities in operation or under consideration, the breadth and depth of information needed to cover the issues related to managed lanes is better suited for a unique document dedicated to managed lane design. Consequently, for additional information on managed lane design and related considerations, refer to *Guidelines for Implementing Managed Lanes*. Additional relevant documents include the most recent versions of the *Freeway Management and Operations Handbook*, the *Priced Managed Lane Guide*, and applicable state and local manuals and guidelines on managed lane design.

It is also recommended that the final sentence of the first paragraph of the "General Considerations" subsection be deleted to eliminate redundancy with the suggested additional section on passenger vehicles.

It is further recommended that additional text be added to the end of Section 10.1, with the text providing information similar to the following:

> Access to managed lane facilities, while using some of the same general design principles as freeway access, has issues and features that are unique to managed lanes. Because there are many variations of managed lane facilities with unique access needs, the breadth and depth of information needed to cover the issues related to managed lane access is better suited for a unique document dedicated to managed lane design. Consequently, for additional information on managed lane access design and related considerations, refer to *Guidelines for Implementing Managed Lanes*. Additional relevant documents include the most recent versions of the *Freeway Management and Operations Handbook*, the *Priced Managed Lane Guide*, and applicable state and local manuals and guidelines on managed lane access design.

Finally, it is recommended that an entry on managed lanes be added to the index and provide cross-references to the two additions suggested above. This entry would replace the current entry entitled "Managed Lanes: A Cross-Cutting Study."

MUTCD

The rapid implementation of managed lanes of all types since 2009 when the MUTCD was last published has exposed many gaps in the document. Because practitioners have had to apply the guidance provided for the first time in the 2009 manual, they have sometimes found it difficult to provide the required amount of regulatory and guide information while maintaining a reasonable sign spreading strategy to avoid driver information overload. The list of research topics in Chapter 6 identifies many needed additions to the manual once appropriate research and engineering judgment have been considered.

One major change to be considered for the MUTCD is to create a new chapter specifically for managed lanes. A separate chapter would gather all guidance and standards for signs, markings, and signals into one reference location. This could make the document easier to use for the practitioner.

Another major change would be to alter the typical layout drawings with general-purpose lane signs illustrated alongside the managed lane signs. Chapter 3G contains a good variety of typical layouts, but all of the illustrations show only the signs for the managed lanes. In practice, however, the challenge is determining how to integrate these signs with general-purpose signs in a way that utilizes available sign supports in an efficient manner while avoiding information overload.

There is still some confusion in the profession regarding the appropriate application of the color purple, particularly with the widespread use of automatic billing by license plate. This practice virtually eliminates the "only vehicles with registered ETC accounts" condition required for the use of purple. The 2013 official interpretation on this subject by FHWA clarified that purple is not needed where license plate capture is in use. There may still be a place for a unique color in managed lane signing, however. Some limited research has indicated that drivers would prefer a different color sign background for managed lane signs to more clearly distinguish them from general-purpose signs. The use of header panels as recommended in the MUTCD presents a subtle distinction between ETC accounts holders, HOVs, and license plate capture systems that is likely lost on most drivers.

There is one inconsistency noted across sections of the MUTCD that should be corrected in future versions. The pavement markings in several of the layouts in Chapter 2G read EXPRESS ONLY (e.g., Fig 2G-26), whereas the pavement marking chapter indicates that text messages should contain the transponder brand name (e.g., Fig 3D-1: EZPASS ONLY). The accompanying text contains a "shall" statement dictating that the ETC account name be used in the word message.

FHWA WEBSITE

The FHWA Office of Operations maintains a website on managed lanes at http://ops.fhwa.dot.gov/freewaymgmt/managed_lanes.htm. The opening page includes a series of resources (see Figure 78). This resource list should include a link to *NCHRP Research Report 835* (*1*).

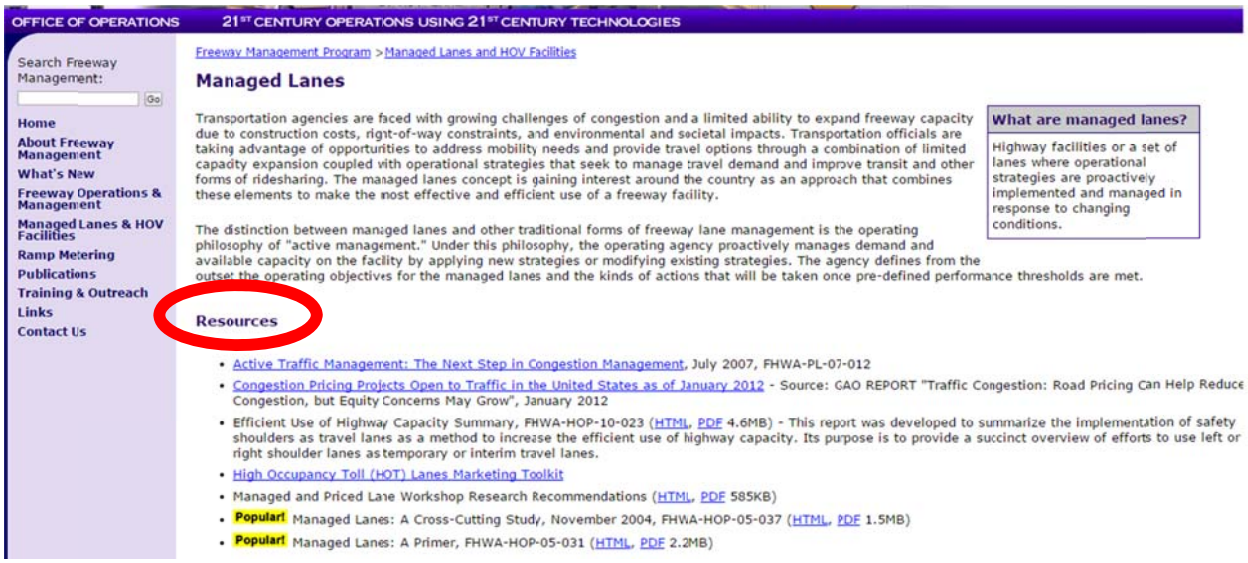


Figure 78. Screenshot of FHWA managed lanes website with resource section circled.

The FHWA website contains a repository of information in separate sections with limited internal links. There are at least three portions of the FHWA website where separate links to *NCHRP Research Report 835: Guidelines for Implementing Managed Lanes* would need to be provided:

- High-occupancy vehicle facilities (http://ops.fhwa.dot.gov/freewaymgmt/hov.htm).
- Managed lanes (http://ops.fhwa.dot.gov/freewaymgmt/managed_lanes.htm).
- Tolling (https://www.fhwa.dot.gov/ipd/fact_sheets/tolling_programs.aspx).

OTHER FHWA PUBLICATIONS

The most important and recent guide that should have a link to *NCHRP Research Report 835* (*1*) is the *Priced Managed Lane Guide* (*36*). This document is a comprehensive guide addressing planning, design, institutional arrangements, and operations for priced managed lane facilities plus operational summaries of each project in operation in 2011. It is one of the few documents available in both printable and electronically indexed formats, making it potentially easy to update with specific chapter links to *NCHRP Research Report 835*. Others listed below do not have this capability.

The next two references of importance are FHWA's *Managed Lanes: A Primer* (*229*) and *Managed Lanes: A Cross-Cutting Study* (*53*). Both are written to avoid the need for updating, although the example projects listed are getting old. A link in each of these to *NCHRP Research Report 835* would be beneficial since these are the orientation documents provided by FHWA on this subject. Hopefully, they will be updated in the near future and better linked to *NCHRP Research Report 835*.

Another relevant FHWA document is the *Freeway Management and Operations Handbook* (*45*). This document is currently being revised, and the research team for NCHRP 15-49 is offering input and edits to the update in development.

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