Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-06/0-4160-23		

4. Title and Subtitle	5. Report Date
MONITORING AND EVALUATING MANAGED LANE FACILITY PERFORMANCE	November 2005
	6. Performing Organization Code
7. Author(s) Jodi L. Carson, Ph.D., P.E.	8. Performing Organization Report No. Report 0-4160-23
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-4160
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: October 2000-August 2005 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Operating Freeways with Managed Lanes
URL: http://tti.tamu.edu/documents/0-4160-23.pdf

16. Abstract

Much of the progress made in advancing the state of the practice in performance monitoring and evaluation has considered general freeway facilities and lacks specificity for managed lane facilities. Managed lane facilities are unique, typically requiring a higher degree of active (sometimes real-time) management, addressing goals and objectives that are inconsistent with the general freeway facility (i.e., revenue generation, person throughput), and accessing an exclusive set of management tools (i.e., gate closures). To address these potential differences between facilities, this investigation was conducted to isolate and document the best performance monitoring and evaluation practices and principles explicitly for managed lane facilities. Despite the novelty of managed lanes as a traffic management strategy, the diversity of managed lane facility types, and the breadth of motivating factors for managed lane implementation, some general consistency in practice was observed with respect to performance monitoring and evaluation. Common goals, objectives, and performance measures were observed across similar facility types. Significant differences were also observed across similar facility types with respect to observed performance outcomes and evaluation methodologies. Differences in observed performance outcomes are likely explained by the variety in facility design (i.e., length of facility, accessibility, etc.) and operation (i.e., eligibility requirements, toll rates, etc.), even within a similar facility type. Differences in the evaluation methodologies used to arrive at these observed performance outcomes are likely reflective of the available resources for analysis at the time of evaluation and the evolving state of analysis methodologies.

17. Key Words	18. Distribution Statement
Monitoring and Evaluation, Performance Measurements, Managed Lanes, HOV, HOT, Truck Restrictions	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	168	

Form DOT F 1700.7 **(8-72) Reproduction of completed page authorized**

MONITORING AND EVALUATING MANAGED LANE FACILITY PERFORMANCE

by

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Report 0-4160-23
Project 0-4160
Project Title: Operating Freeways with Managed Lanes

Performed in Cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

September 2005

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DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. This project was conducted in cooperation with the Texas Department of Transportation (TxDOT) and the U.S. Department of Transportation, Federal Highway Administration (FHWA). The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The engineers in charge of the overall project were Beverly T. Kuhn (Texas P.E. #80308) and Ginger Daniels Goodin (Texas P.E. #64560). The engineer leading this task was Jodi L. Carson (Texas P.E. #94536).

The U.S. Government and the State of Texas do not endorse products of manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. Special thanks are extended to the following members of the Project Monitoring Committee, both past and present, for their leadership, time, efforts, and contributions:

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CHAPTER 1:
INTRODUCTION

In developed urban areas, the provision of sufficient roadway capacity through traditional capital facility expansion is challenged by ever-increasing travel demand, site development, cost, neighborhood impacts, environmental concerns, and other factors. Like other transportation agencies nationwide, the Texas Department of Transportation (TxDOT) is looking to alternative methods to better manage traffic flow and improve the efficiency and operation of existing roadway networks [Texas Transportation Institute (TTI) 2002]. Managed lanes may offer such an alternative.

Managed lanes encompass a variety of facilities and operational strategies that may be adjusted throughout the day or week to better accommodate travel conditions. Managed lanes utilize time-of-day restrictions, vehicle occupancy restrictions, vehicle type restrictions, value pricing, or a combination of these strategies to keep traffic flowing (TTI 2002). In addition to maximizing use of the existing freeway capacity and managing traffic demand, managed lanes offer travelers choices, may improve safety, and may generate revenue, depending upon the operational strategies employed (TTI 2002).

Because managed lanes represent a new way of doing business for transportation agencies, TTI, assisted by Texas Southern University, is conducting a multi-year project entitled *Operating Freeways with Managed Lanes* to investigate the complex and interrelated issues surrounding safe and efficient operation of managed lanes and to develop a *Managed Lanes Manual* to help TxDOT and other transportation agencies make informed planning, design, and operational decisions when considering these facilities for their jurisdiction (TTI 2002). This project is cooperatively sponsored by TxDOT and the Federal Highway Administration (FHWA) and will address such questions as:

Planning Managed Lane Facilities

- What are the operational options available for a managed lane facility?
- How does an intended user group(s) affect its design and operations?
- What defines a successful managed lane project?
- How can I fund and finance a managed lane project?
- How do I market a managed lane project to help make it a success?

- How do I integrate other key agencies (transit, toll, law enforcement, etc.) into a managed lane project to help overcome institutional issues and barriers?
- Are there any interim or temporary uses for a managed lane facility?

Designing Managed Lanes Facilities

- How do I design a managed lane facility to handle a selected user group?
- How can I design a facility to be flexible for future needs?
- What safety issues do I need to be aware of when designing a facility?
- What interoperability issues do I need to be aware of when designing a facility?
- What information do users need to make decisions about using a managed lane facility?
- What approaches to delivering user information provide that information appropriately?

Operating Managed Lanes Facilities

- What is the best way to enforce a managed lane facility?
- How do I handle incidents on a managed lane facility?
- What staff do I need to manage a managed lane facility and what training do they need?
- How do I evaluate and monitor a managed lane facility to determine success? (TTI 2002)

As part of this larger study, this report responds to the operational-related questions of monitoring and evaluating managed lane facility performance. A description of the problem, the task objectives, the investigation methodology, and the report purpose and contents are provided below.

PROBLEM DESCRIPTION

A successful performance monitoring and evaluation program generally comprises six indistinct and overlapping steps:

1. setting goals and objectives that reflect the program or system's desired performance and are consistent with agency or regional priorities;
2. identifying appropriate performance measures to accurately evaluate attainment of the goals and objectives;

3. identifying required data and sources to support calculation of the performance measures;
4. defining appropriate evaluation methods within the constraints of data availability and staff training;
5. defining an appropriate schedule for on-going, periodic monitoring of the system; and
6. reporting the results in a usable and easily understood format (Neudorff et al. 2003).

Successful performance monitoring and evaluation activities support an agency's provision of day-to-day services, direct facility and administrative management decisions, and guide short- and long-range planning efforts.

Despite not so recent legislative or regulatory mandates [i.e., the Transportation Equity Act for the 21st Century (TEA-21) requiring performance monitoring as an eligibility criteria for federal funding of transportation projects], transportation agencies have been challenged to adequately monitor and evaluate transportation facility performance. Neudorff et al. (2003) characterized several of these challenges as follows:

- current *Highway Capacity Manual* (*HCM 2000*)-based levels of service (LOS) measures don't adequately capture the effects of operational strategies, which are often more subtle than capacity expansion projects;
- the concept of a "peak hour" has been rendered irrelevant by travel patterns that have led to "peak periods;"
- the proper perspective for measuring performance—the view of the user (traveler) versus the view from the facility—is under debate;
- the concept of "reliability" is growing in importance; the variability that occurs day-to-day is important;
- traditional monitoring data, which are scattered and sampled, lack the resolution to capture the effects of more modest operational improvements.

Much of the progress made in addressing these challenges, developing performance measures, and refining evaluation methods has considered general freeway facilities, as documented in the *Freeway Management and Operations Handbook* (Neudorff et al. 2003), the *Performance Measurement Initiative* [National Transportation Operations Coalition (NTOC) 2005], and most recently, the *Guide to Effective Freeway Performance Measurement, Version*

1.0 [National Cooperative Highway Research Program (NCHRP) 2004]. These reference guides address site-specific to corridor-level operations analysis, alternative investments analysis, area-wide planning, and public information studies for a variety of strategies used for freeway management and operations.

While these guides are comprehensive in topic, they lack specificity for managed lane facilities. Managed lane facilities are unique, typically requiring a higher degree of active (sometimes real-time) management, addressing goals and objectives that are inconsistent with the general freeway facility (i.e., revenue generation, person rather than vehicle throughput, etc.), and accessing an exclusive set of management tools (i.e., gate closures, etc.). These differences may affect how managed lane facility performance is successfully monitored and evaluated.

OBJECTIVES

To address the potential differences between managed lane facilities and general freeway facilities, this investigation was conducted to isolate and document the best performance monitoring and evaluation practices and principles explicitly for managed lane facilities. More specifically, the objectives of this task were to:

- identify positive performance monitoring and evaluation practices for managed lanes (i.e., in published literature or observed practice) that could be recommended for widespread implementation;
- document reportable managed lane benefits that may guide the development of performance "benchmarks" for monitoring and evaluation;
- identify and describe any issues for consideration surrounding performance monitoring and evaluation practices for managed lanes; and
- assimilate this information into recommended guidelines addressing all aspects of managed lane facility performance monitoring and evaluation.

This information will form the basis of the recommendations contained in the *Managed Lanes Manual* developed for TxDOT and FHWA.

METHODOLOGY

To accomplish the objectives of this task related to the monitoring and evaluation of managed lane performance, researchers conducted a review of published literature and ongoing research to (1) identify positive practices that could be recommended for widespread implementation, (2) identify and describe any issues for consideration surrounding these practices, and (3) document reportable benefits to support development of performance "benchmarks."

Researchers primarily utilized the Transportation Research Information Services (TRIS) online database and the Transportation Research Board's Research in Progress (RIP) database to identify appropriate published literature and ongoing research. The novelty of managed lanes as a traffic management strategy, the diversity of managed lane facility types [i.e., high-occupancy vehicle (HOV) lanes, exclusive truck lanes, etc.], and the breadth of motivating factors for managed lane implementation (i.e., to improve mobility and congestion, reliability, accessibility, safety, environmental impact, system preservation, organizational efficiency, etc.) challenged identification and selection/reduction of pertinent literature. Nonetheless, three general types of information emerged:

- collective guidelines related to overall freeway performance monitoring and evaluation,
- collective guidelines related to singular managed lane facility (i.e., HOV lane facilities) performance monitoring and evaluation, and
- site-specific findings (i.e., national practice) related to managed lane facility performance monitoring and evaluation.

Collective Guidelines for Overall Freeway Performance Monitoring and Evaluation

In response largely to TEA-21's requirements for performance monitoring as an eligibility criterion for receipt of federal funding, a number of studies were conducted in the 1990s that focused on guiding or enhancing these activities. These efforts focused almost exclusively on (1) defining appropriate performance measures, (2) improving data quality and the efficiency with which data are captured, and (3) integrating these performance data into the decision-making process to support facility operations and management or planning.

These seminal studies culminated in the development of national guidelines for general freeway performance monitoring and evaluation. The *Freeway Management and Operations Handbook* (Neudorff et al. 2003) considers a broader spectrum of topics but devotes one chapter to describing best practices for freeway performance monitoring and evaluation. In addition, NTOC (2005) recently published results from its *Performance Measurement Initiative* that detail a short list of recommended performance measures that can be used for internal agency management, external communications, and comparative measurement. Most recently and currently under development, *NCHRP 3-68: Guide to Effective Freeway Performance Measurement, Interim Report* (NCHRP 2004) provides comprehensive direction for defining and utilizing freeway performance measures and developing a comprehensive freeway performance management program. This investigation relied heavily upon the guidance provided in these recent documents to ensure consistency with national performance monitoring and evaluation guidelines and to reflect prior lessons learned for these activities.

Concurrently with the development of collective guidelines for overall freeway performance monitoring and evaluation, a number of state departments of transportation were undertaking their own efforts to develop performance monitoring guidelines tailored to their specific needs. Shaw (2003) comprehensively documented state-level performance monitoring and evaluation practices in *NCHRP Synthesis 311: Performance Measures of Operational Effectiveness for Highway Segments and Systems*. State-level programs described in this synthesis review include Arizona, California, Delaware, Florida, Maryland, Minnesota, New York, Texas, Virginia, and Washington. These state-level observations helped to temper the collective recommendations for performance monitoring and evaluation by demonstrating activities feasible for implementation.

Additional guidance, focused on some aspect of facility performance, is also available. For example, FHWA publishes the *TEA-21 Evaluation Guidelines* (www.fhwaedl.fhwa.dot.gov/evaluation/eguide_tea21.htm) and the *ITS Evaluation Resource Guide* (www.its.dot.gov/evaluation/eguide_resource.htm) to support the evaluation of technology-related facility improvements. More focused documents, such as these, were not extensively considered as part of this investigation.

Collective Guidelines for Managed Lane Facility Performance Monitoring and Evaluation

Only two documents were uncovered that provided collective guidelines for managed lane facility performance and monitoring: (1) *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities* (Turnbull et al. 1991) and (2) *High-occupancy Vehicle Monitoring and Evaluation Framework* (Bracewell et al. 1999). Not surprisingly, both documents focus on HOV lane facilities; HOV lane facilities, more than other type of managed lane facility, experienced early and widespread implementation and, hence, have been the subject of significant study.

National Practices for Managed Lane Facility Performance Monitoring and Evaluation

With the exception of the two HOV-related documents referenced above, information specific to managed lane facilities was largely limited to site-specific evaluation studies. Much of the information considered managed lane facilities currently in operation (i.e., HOV lanes, truck lane restrictions) or in operation as a demonstration project; although researchers found a number of studies that considered the feasibility of various managed lane facilities prior to implementation [i.e., valued-priced and high-occupancy toll (HOT) lanes and exclusive bus and truck lanes]. The results of these evaluation studies were used primarily to establish a range of performance targets by facility type but also to identify and confirm the appropriateness of various performance monitoring and evaluation activities as specifically applied to managed lane facilities.

REPORT PURPOSE AND CONTENTS

Following this introductory information, Chapter 2 overviews managed lane facilities and their characteristics. Chapter 3 outlines the overall performance monitoring and evaluation process, including any pertinent recommendations from the national guidance documents. Chapter 4 summarizes guidelines and national practice related specifically to monitoring and evaluating managed lane performance, including any reportable benefits. Assimilating the information provided in Chapters 3 and 4, this report concludes, in Chapter 5, with a summary of findings and recommendations related to managed lane facility performance monitoring and evaluation.

CHAPTER 2:
MANAGED LANE FACILITIES

"Managed lanes" are defined broadly and differently from agency to agency, including or excluding certain facilities or strategies. FHWA defines managed lanes as follows:

> *Highway facilities or a set of lanes in which operational strategies are implemented and managed (in real time) in response to changing conditions* (Obenberger 2004).

Alternatively, TXDOT provides the following definition:

> *A managed lane facility is one that increases freeway efficiency by packaging various operational and design actions. Lane management operations may be adjusted at any time to better match regional goals* (TTI 2002).

Such breadth and variability in definition, leading to breadth and variability in the facility types and strategies for consideration, challenges the provision of general guidelines for performance monitoring and evaluation.

FACILITY TYPES

This investigation will address the following types of managed lane facilities:

- high-occupancy vehicle lanes;
- value-priced and high occupancy toll lanes;
- exclusive lanes, with a focus on passengers or freight;
- mixed-flow separation/bypass lanes, with a focus on passengers or freight;
- lane restrictions, with a focus on freight, and
- dual facilities.

Additional or different classifications of managed lane facilities may be defined elsewhere.

High-occupancy Vehicle Lanes

The intent of HOV lanes is to increase the person-moving capacity of the existing infrastructure by providing travel time advantages to high-occupancy vehicles. HOV lanes include one or more lanes that are restricted to vehicles with a specified occupancy, including carpools, vanpools, and/or buses. HOV lane facilities can operate as (1) separated two-way or reversible, (2) concurrent, or (3) contraflow, and can vary by occupancy level [i.e., buses, vanpools, 3+ carpools (carrying three or more passengers), 2+ carpools (carrying two or more passengers), etc.] and time of operation (i.e., 24 hours a day, extended hours, or peak travel periods) (Kuhn et al. 2003).

Separated Two-way or Reversible HOV Lanes

Separated two-way HOV lanes are typically within a freeway right-of-way but physically separated from the general-purpose lanes by concrete barriers or wide painted buffers. Limited access points are provided to eligible vehicles that generally include buses, vanpools, and carpools. Separated two-way HOV lanes are easier to enforce because of the access limitations (TTI et al. 1998).

Similarly, reversible HOV lanes are typically built within the freeway right-of-way and physically separated from the general-purpose lanes. Reversible HOV lanes are intended for areas with high directional traffic splits to accommodate traffic going toward the central business district in the morning and in the outbound direction in the evening. This type of facility requires daily setup to switch travel direction (TTI et al. 1998).

A number of additional criticisms have been cited for reversible lane operations:

- violation of driver expectancy,
- safety issues,
- extensive manpower for implementation,
- problems in converting the roadway back to two-way flow without creating bottlenecks, and
- dangerous geometric implications (i.e., adverse superelevation, limited sight distance, etc.) (Ullman et al. 1993, Wohlschlaeger and Ullman 1991, Ullman and Trout 1991).

Concurrent HOV Lanes

Concurrent-flow HOV lanes are not physically separated from the general-purpose lanes; access may be continuous or limited to specific points. Concurrent HOV lanes are usually located on the inside lane, but they may also be positioned on the outside lane. Concurrent HOV lanes are generally used by buses, vanpools, and carpools moving in the same direction as the adjacent general-purpose lanes. Continuous access to concurrent HOV lanes challenges enforcement efforts (TTI et al. 1998).

Contraflow HOV Lanes

Contraflow HOV lanes operate in the off-peak direction of travel and are designated for use by eligible buses, vanpools, and carpools traveling in the peak direction. Contraflow HOV lanes are most often separated from the adjacent general-purpose lanes by some type of changeable treatment such as a moveable concrete barriers, plastic posts, or pylons. This changeable separation allows the lane to revert to normal operation (i.e., concurrent HOV, general purpose, etc.) outside of the peak travel periods. Operating costs for contraflow HOV lanes may be higher than those of other types of HOV facilities, and safety is of greater concern (TTI et al. 1998).

Value-priced and High Occupancy Toll Lanes

Value-priced and high occupancy toll lanes are intended to maximize the use of underutilized capacity in a managed lane without exceeding its capacity and creating congestion. HOT lanes allow lower occupancy vehicles to use the existing HOV lanes if they are willing to pay a toll. Variations of HOT lanes include value-priced, value express, and fast and intertwined regular (FAIR) lanes, which may or may not be occupancy driven and typically resemble more traditional toll road facilities. Dynamic toll pricing supports the management of facilities (Kuhn et al. 2003). In some instances, value-pricing strategies have focused on potential benefits for commercial vehicles, although the success of these efforts has been inconclusive (Supernak et al. 1998).

Because value-priced and HOT lanes take advantage of existing HOV lane facilities, these lanes may or may not be physically separated from the general purpose facility; may operate continuously, during extended hours, or only during the peak travel periods; and may have different vehicle occupancy eligibility criteria.

Exclusive Lanes

Exclusive lanes provide a dedicated operational lane to certain vehicles, usually designated by vehicle type and including buses or large trucks. Unlike lane restrictions that generally restrict trucks or buses to or from certain lanes on a facility, exclusive lanes provide a physically separated facility reserved for use by trucks or buses (in some instances, other vehicles are allowed to use these lanes but the traffic volumes are generally low and do not impede truck or bus travel). Bus-only lanes seek to attract ridership through decreased delay and high travel time reliability. Truck-only lanes seek to decrease delay, reduce conflicts with passenger cars, and increase safety through physical separation. Exclusive lanes typically operate continuously (Kuhn et al. 2003).

Mixed-flow Separation/Bypass Lanes

The operational intent of mixed-flow separation/bypass lanes is twofold: (1) to improve safety through congested or turbulent traffic flow segments (i.e., a weaving area with significant congestion or a significant grade with a high percent of truck traffic) and (2) to provide time-savings benefits to identified user groups (i.e., priority access for trucks or buses around ramp metering, toll plazas, ferry queues, etc.). Mixed-flow separation and bypass lane facilities typically comprise a separate lane alongside the general-purpose lanes. In general, these lanes are short in length and intended only to bypass spot-location delays (Kuhn et al. 2003).

Lane Restrictions

Lane restrictions limit certain types of vehicles, most commonly large trucks, to specified lanes. Lane restrictions for large trucks may improve operations, reduce accidents, reduce pavement damage, and improve construction zone activities where large percentages of trucks degrade speed, comfort, and convenience. Because restricted lanes are still open for travel by other types of vehicles, these lanes are not separated from the general purpose travel lanes. Lane restrictions may be in effect continuously, during extended periods of the day, or only during the peak travel periods. However, access to these restricted lanes by other types of vehicles is continuous.

Dual Facilities

Dual facilities provide physically separated inner and outer roadways in each direction with the inner roadway reserved for light vehicles or cars only and the outer road open to all vehicles, including large trucks and buses. By allowing separation of vehicles with different operating characteristics (i.e., cars and light vehicles versus large trucks and buses), dual facilities serve to reduce congestion and improve safety. Dual facilities operate continuously (Kuhn et al. 2003).

FACILITY CHARACTERISTICS AFFECTING PERFORMANCE

To accurately direct performance targets and assess observed performance, transportation agencies should consider the original motivating goals and objectives that led to the implementation of the managed lane facility (i.e., reduce congestion, improve reliability, and improve safety), as well as the facility characteristics. Facility characteristics that are most influential in affecting managed lane facility performance include:

- accessibility, including the type and degree of managed lane separation from the general purpose facility and the number and frequency of ingress/egress points;
- hours of operation (i.e., continuous, extended hours, or peak travel periods only); and
- eligibility criteria, including vehicle types, vehicle occupancies, toll structures, etc.

Motivating Goals and Objectives

The implementation of a managed lane facility can be motivated by a number of factors. Most commonly, the intent of managed lanes is to (1) improve congestion and/or travel time reliability, (2) improve safety, or (3) generate revenue. Secondary goals and objectives may relate to improving accessibility, reducing environmental impacts, preserving the pavement infrastructure, or enhancing an agency's organizational efficiency. Managed lane facilities or operational strategies that incorporate some aspect of occupancy requirement (i.e., 2+ carpools and 3+ carpools) or target high-occupancy vehicles, such as buses or vans, are largely motivated by efforts to improve congestion and/or travel time reliability. Strategies that focus on large trucks are likely intended to improve safety, with secondary concerns for improving congestion and/or travel time reliability and reducing or distributing pavement wear. Value-priced and HOT lanes are intended to improve congestion and/or travel time reliability across the facility by making use of underutilized capacity in the managed lane facility; value pricing has the dual benefit of managing congestion while generating revenue for transportation agencies.

Recognizing the original motivating goals and objectives that led to the implementation of the managed lane facility, and its subsequent design and operational characteristics, will better direct the selection of meaningful performance measures.

Accessibility

The accessibility of the managed lane facility from the general purpose facility directly impacts the potential for benefit and, hence, its performance. In particular, the type and degree of separation between the facilities and the frequency of ingress/egress points are important. Four common methods are employed for providing access to managed lane facilities: (1) direct merges, (2) slip ramps, (3) direct access ramps, and (4) direct connections from other managed lanes (Murray et al. 2000).

Direct Merges

The direct merge approach allows vehicles to enter a managed lane facility from an adjacent general-purpose lane (i.e., continuous access). This method is normally used with concurrent-flow HOV lanes, concurrent-flow value-priced or HOT lanes, and lane restrictions. Direct merges provide the greatest degree of accessibility to a managed lane and, hence, provide the greatest potential for utilization. Direct merges also experience the greatest number of conflicts with general purpose traffic when merging and present difficulty in enforcement when standard operations resume (Murray et al. 2000). These characteristics related to accessibility and safety should be recognized when setting performance targets and reviewing observed performance.

Slip Ramps

Slip ramps provide access to barrier-separated managed lane facilities by providing a gap in the barrier and permitting either the ingress or egress of traffic (i.e., eligible users during standard operation and general purpose traffic or others during interim use). Slip ramps can provide access to separated two-way or reversible HOV, value-priced, or HOT lanes; contraflow HOV, value-priced, or HOT lanes; exclusive lanes; mixed-flow separation/bypass lanes; or dual facilities that are barrier separated. Because slip ramps provide only periodic access to the managed lane facility, accessibility to the lane is somewhat limited. At ingress and egress points, merging with the adjacent freeway lanes may cause some conflicts (Murray et al. 2000). Again, these characteristics related to accessibility and safety should be recognized when setting performance targets and when reviewing observed performance.

Direct Access Ramps

For grade-separated facilities, direct access or grade-separated ramps allow exclusive access for eligible managed lane users. Direct access ramps can connect the managed lane facility with adjacent roads, park-and-ride lots, transit stations, ports, freight terminals, etc. Subsequent performance measures should consider the unique benefits resulting from limited access and distinct destinations under standard managed lane operations (Murray et al. 2000).

Direct Connections from Other Managed Lane Facilities

Managed lanes on one freeway may directly connect to managed lanes on another freeway. This connection offers travel-time savings that would not be available if the vehicles were required to exit the managed lane facility on one freeway, merge with general purpose traffic, use the freeway interchange, and enter the other managed lane facility. The lower merging requirements are another benefit to this method (Murray et al. 2000). A clear understanding of these unique time savings and safety related benefits will better direct the selection of meaningful performance measures.

Hours of Operation

Managed lanes are most often operated (1) continuously, 24 hours a day, (2) during extended hours, or (3) during the peak travel period only. Performance measures should reflect temporal differences in observed performance across the various facility operational periods.

Continuous (24 hours)

Some managed lane facilities are restricted 24 hours a day to provide eligible users with continuous travel-time savings and reliability. This approach simplifies enforcement and reduces motorist confusion but encourages the potential public perception that the lanes are not sufficiently utilized (Murray et al. 2000).

Extended Hours

Typical hours of operation under the extended hours strategy are 6:00 a.m.–11:00 a.m. and 3:00 p.m.–7:00 p.m., which correspond to periods of high congestion. This strategy is especially appropriate for contraflow HOV, value-priced and HOT lanes, and separated two-way or reversible HOV lanes because of the preparation required for the facility. Potential disadvantages of extended operating hours include motorist confusion, enforcement difficulty, and signing and pavement marking requirements (Murray et al. 2000).

Peak Travel Period Only

The minimum number of hours that a managed lane facility can operate is during the peak period only. The peak period usually falls between 6:00 a.m. and 9:00 a.m. and between 4:00 p.m. and 6:00 p.m. The types of managed lane facilities that normally operate under this plan are contraflow HOV, value-priced, and HOT lanes and concurrent-flow HOV, value-priced, and HOT lanes (Murray et al. 2000).

Related to the hours of operation is the use of the facility in the non-operating periods. Managed lane facilities with extended hours or peak period-only hours provide an opportunity for other vehicles to use the lanes at other times. For example, concurrent-flow HOV lanes may convert back to general-purpose lanes or shoulders during non-peak period. Contraflow HOV lanes may revert back to the mixed traffic lanes during the off periods. About half of the nation's HOV lanes operate part-time, either during extended hours or peak periods, with the lanes reverting to general traffic use when they are not restricted. The remaining half of the HOV facilities operate on a continuous 24-hour basis (TTI et al. 1998).

Eligibility

Managed lane use eligibility under standard operating conditions is defined by vehicle type, vehicle occupancy, or a willingness to pay a toll. The eligibility criteria largely control the amount of excess or underutilized capacity available in the managed lane. Performance measures related to lane utilization should directly consider the effects of eligibility.

The type of vehicles eligible to use a managed lane facility is also indicative of the level of facility design. Among the vehicles that could be permitted on the facility are buses, vans, cars, light trucks, motorcycles, commercial vehicles and trucks, taxis, airport shuttles, and emergency vehicles.

CHAPTER 3:
GENERAL GUIDELINES FOR PERFORMANCE MONITORING AND EVALUATION

As mentioned previously, a successful performance monitoring and evaluation program generally comprises six indistinct and overlapping steps:

1. setting goals and objectives that reflect the program or system's desired performance, consistent with agency or regional priorities;
2. identifying appropriate performance measures to accurately evaluate attainment of the goals and objectives;
3. identifying data and sources to support calculation of the performance measures;
4. defining appropriate evaluation methods within the constraints of data availability and staff training;
5. defining an appropriate schedule for on-going, periodic system monitoring; and
6. reporting the results in a usable and easily understood format (Neudorff et al. 2003).

Several recent publications comprehensively address the performance monitoring and evaluation process for general freeway facilities including:

- *Freeway Management and Operations Handbook* (Neudorff et al. 2003);
- *Performance Measurement Initiative* (NTOC 2005); and
- *NCHRP 3-68: Guide to Effective Freeway Performance Measurement* (2004);

and, to a lesser extent:

- *NCHRP Synthesis 311: Performance Measures of Operational Effectiveness for Highway Segments and Systems* (Shaw 2003);
- *TEA-21 Evaluation Guidelines* and *ITS Evaluation Resource Guide* (www.fhwaedl.fhwa.dot.gov/evaluation/eguide_tea21.htm, www.its.dot.gov/evaluation/eguide_resource.htm); and
- *Decision Support Methodology for Selecting Traffic Analysis Tools* (FHWA 2003).

Considering each step in the six-step performance monitoring and evaluation process, this chapter summarizes general guidelines and pertinent recommendations from key national guidance documents applicable to managed lane facilities. For additional detail on performance monitoring activities, the reader is referred to the original information source.

GOALS AND OBJECTIVES

Setting measurable goals and objectives is a first step in establishing a successful program of performance monitoring and evaluation. For transportation facilities, goals and objectives typically focus on:

- mobility and congestion,
- reliability,
- accessibility,
- safety,
- environmental impacts,
- system preservation, and/or
- organizational efficiency (Neudorff et al. 2003).

With these various focus areas in mind, Neudorff et al. (2003) suggests that to be successful, developed goals and objectives should:

- be measurable and quantifiable, adequately describing changes in operation;
- consider performance at the system, project, agency, regional, or statewide level and involve the public, local business interests, elected officials, and agency personnel;
- drive the data to be collected, not be driven by data availability;
- consider qualitative (i.e., related to customer satisfaction) goals; and
- prioritize conflicting goals (i.e., system preservation goals may require an increase in maintenance expenditures while agency efficiency goals seek to minimize maintenance costs).

Table 1 provides typical goals and objectives for general freeway facilities.

PERFORMANCE MEASURES

Following the definition of measurable goals and objectives, appropriate measures for capturing changes in performance should be identified. Successful performance measure characteristics and emerging trends in performance measurement are described below. Culminating from these collective guidelines and observed trends, typical and recommended performance measures from various sources are provided.

Table 1. Typical Goals and Objectives for Freeway Facilities (Neudorff et al. 2003).

GOAL AREA	GOALS	OBJECTIVES
MOBILITY/ CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility	• Increase average travel speeds (without exceeding safe operating speeds)
		• Decrease average travel times
		• Decrease delay
		• Increase throughput
		• Decrease extent and duration of congestion (LOS E or F)
		• Decrease restricted lane (i.e., HOV, HOT lanes) violators
RELIABILITY	Increase reliability during recurring and nonrecurring congestion	• Decrease travel speed or travel time variation
		• Increase "on-time" transit performance
ACCESSIBILITY	Increase overall accessibility while reducing vehicular congestion	• Maintain or increase facility lane-miles
		• Maintain or increase access to employment (home to work commuters)
		• Decrease the number and duration of facility restrictions (seasonal weight or low clearance restrictions, etc.)
SAFETY	Increase overall safety levels	• Decrease the frequency and severity of incidents
		• Decrease average incident duration
		• Decrease secondary incidents
		• Increase throughput
ENVIRONMENTAL IMPACTS	Decrease overall impacts to the environment and resources	• Decrease fuel consumption
		• Increase air quality/decrease pollutants
		• Decrease noise pollution
		• Decrease hazardous material incidents
SYSTEM PRESERVATION	Maintain or increase overall system service life	• Decrease deficient facilities
ORGANIZATIONAL EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel	• Maintain or increase network coverage and system utilization
		• Increase quality of staff activities
		• Increase quantity (productivity) of staff activities
		• Increase system performance and functionality
		• Increase customer satisfaction ratings
		• Minimize costs
		• Maximize revenue

Basic Principles in Performance Measurement

In addition to the success factors for developing goals and objectives cited above, Neudorff et al. (2003) identified several basic principles that help to ensure development of a successful set of performance measures and, subsequently, a successful monitoring and evaluation program. Performance measures should be:

- limited in number to prevent data collection and analytical requirements from overwhelming an agency's resources or decision-makers;
- simple and understandable with consistent definitions and interpretations to address the needs of a wide-ranging audience, while still achieving the required precision, accuracy, and detail to facilitate system or program improvement;
- easily captured either automatically using various technologies or manually with minimal manual data entry and processing to produce usable results;
- sensitive to change, able to adequately capture observed changes in system or program performance;
- consistent with staff skills (simplistic evaluation methods with accurate results are preferred over advanced methods that may be erroneous if staff are not adequately trained);
- consistent in time frame with decision-making needs, ranging from real-time to long-term; and
- geographically appropriate with decision-making needs, ranging from corridor-specific to region-wide, statewide, or even nationwide.

Emerging Trends in Freeway Performance Measurement

Despite the number of and variety in potential performance measures, NCHRP (2004) has identified several emerging trends that are evident and consistent, reflected in the more recently recommended performance metrics. These emerging "principles" for performance measurement, with a focus on freeway facilities, are as follows:

- mobility measures should be based on travel time (travel time, or other similar derivatives of speed and delay, is easily understood by practitioners and the public and is applicable to both the user and facility perspectives of performance);

- multiple metrics should be used to report performance;
- traditional Highway Capacity Manual (HCM)-based performance measures [volume to capacity (V/C) ratio and LOS] should not be ignored but should serve as supplementary, not primary, measures of performance in most cases;
- both vehicle-based and person-based performance measures should be developed (person-based measures provide a "mode-neutral" way of comparing alternatives);
- both mobility and efficiency performance measures should be developed with improvements in efficiency linked to positive changes in mobility;
- customer satisfaction measures should be included;
- three dimensions of freeway congestion should be tracked with mobility measures: source of congestion, temporal aspects, and spatial detail; and
- the buffer index - the amount of extra time needed to be "on-time" 95 percent of the time - is emerging as the preferred reliability measure.

Typical Performance Measures for Freeway Facilities

Building upon the information provided in Table 1 and reflecting the basic and emerging principles for successful performance monitoring and evaluation described above, Table 2 provides related performance measures for each of the typical areas of focus, goals, and objectives for a freeway facility (Neudorff et al. 2003). Other variations of this list have been developed. Meyer (1995) proposed a similar list of performance measures related to mobility and congestion, accessibility, safety, environmental impacts, system preservation, and organizational efficiency but added performance measures related to economic development and quality of life to support performance-based transportation planning. Shaw (2003) developed a reduced list of recommended performance measures based on the highest scores, consistency of use, and "their ability to serve as a foundation for other commonly reported measures, such as congestion index" (see Table 3).

NCHRP's *Guide to Effective Freeway Performance Measurement* (2004) provides four separate lists of potential performance measures depending on application:

- operation, emergency response, and traveler information application;
- transportation planning, land use planning , national freeway system evaluation, and transportation programming applications;

Table 2. Typical Performance Measures for Freeway Facilities (Neudorff et al. 2003).

AREA/GOALS		OBJECTIVES	PERFORMANCE MEASURES
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility	• Increase average travel speeds (without exceeding safe operating speeds)	• Average speed [by lane (HOV and other lanes) across facility] • Average speed [vehicle miles of travel (VMT), person miles of travel (PMT), truck miles of travel (TMT)] • Average system-wide speed [= VMT/vehicle hours of travel (VHT)] • Average running speed [= (segment length/travel time) – stop delay] • Congestion Index (percent of posted speed) • Percent of highway miles with peak period speeds <45 mph • Number of low speed trips [<½ free-flow speed (FFS)] by time of day, trip type
		• Decrease average travel times	• Average travel time from origin to destination • Travel time median and 95th percentile • Travel time rate (minutes per mile) • Travel time savings per mile • HOV lane travel time performance standards success rate • Customer perceptions on travel time
		• Decrease delay	• Average delay (recurring, incident based) • Average delay (per day, annually) • Average delay (per vehicle, per person, per ton-mile) • Average delay [VHT, person hours of travel (PHT), truck hours of travel (THT)] • Average stop delay (<3 mph) • Delay rate in minutes per mile • Percent change in delay (recurring and incident based)
		• Increase throughput	• Total, daily, and hourly facility volume (general purpose, HOV, other) • Total, daily, and hourly facility volume (vehicle, person, truck volumes) • Daily and hourly volume on HOV facilities (vehicle, person volumes) • Transit ridership • Vehicle occupancy (persons per vehicle) • Percent peak period volume (vehicle, person, truck volumes) • VHT, PHT, or THT • VMT, PMT, or TMT
		• Decrease extent and duration of congestion (LOS E or F)	• Density (vehicles per hour per lane, peak periods) • V/C ratio (peak periods) • Level of service (peak periods) • Queuing (frequency, length, speed, duration, growth rate) • Total system at LOS E or F (per lane-mile, VMT, PMT, TMT) • Percent of system at LOS E or F (per lane-mile, VMT, PMT, TMT) • Frequency of LOS E or F by location • Lane-mile-hours at LOS E or F • Percent of travel at LOS E or F
		• Decrease HOV lane violators	• Percent of HOV lane violators

Table 2. Typical Performance Measures for Freeway Facilities (Continued, Neudorff et al. 2003).

	AREA/GOALS	OBJECTIVES	PERFORMANCE MEASURES
RELIABILITY	Increase reliability during recurring and nonrecurring congestion	• Decrease travel speed or travel time variation	• Variance of average travel time or speed (coefficient of variation) • Reliability factor • Misery index
		• Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor, major trip) • Percent of trips arriving acceptable time window
ACCESSIBILITY	Increase overall accessibility while reducing vehicular congestion	• Maintain or increase facility lane-miles	• Total facility lane-miles (general purpose, HOV, other) • Net change in facility lane-miles (general purpose, HOV, other)
		• Maintain or increase access to employment (home to work commuters)	• Percent peak work trips within __ minutes of home • Percent employment sites within __ miles of major highway
		• Decrease number and duration of facility restrictions (weight, clearance, etc.)	• Number of bridges with vertical clearance less than __ feet • Bridges with seasonal weight restrictions (number, percent and duration)
SAFETY	Increase overall safety levels	• Decrease the frequency and severity of incidents	• Number of high incident locations • Number of incidents (by type, location) • Number of incidents (VMT, PMT, TMT) • Number of fatalities and injuries (by incident type, location) • Incident severity
		• Decrease average incident duration	• Average incident duration • Response time to incidents (by type, location)
		• Decrease secondary incidents	• Number of secondary incidents
		• Increase throughput	• Evacuation clearance time • Total, daily, and hourly facility volume (vehicle, person, truck volumes)
ENVIRONMENTAL IMPACT	Decrease overall impacts to the environment and resources	• Decrease fuel consumption	• Fuel consumption (PMT, VMT, TMT)
		• Increase air quality/decrease pollutants	• Tons of pollutants • Number of days in air quality non-compliance
		• Decrease noise pollution	• Percent of population exposed to noise above a certain threshold
		• Decrease hazardous material incidents	• Number of incidents involving hazardous waste
SYSTEM PRESERVATION	Maintain or increase overall system service life	• Decrease deficient facilities	• Percent of VMT on roads with deficient ride quality • Percent of roads and bridges below a standard condition • Remaining service life • Maintenance costs per year • Roughness index for pavements • Percent of roadway pavement rated good or better

Table 2. Typical Performance Measures for Freeway Facilities (Continued, Neudorff et al. 2003).

AREA/GOALS		OBJECTIVES	PERFORMANCE MEASURES
ORGANIZATIONAL EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel	• Maintain or increase network coverage and system utilization	• Number of systems deployed (by type, location) • Miles of coverage • Number of times each system is utilized
		• Increase quality of staff activities	• Staff availability • Number of hours worked (operators, drivers) • Number of on-the-job injuries • Percent of employees with >32 hrs of training • Percent of mandatory supervisor training • Years of experience • Turnover rate
		• Increase quantity (productivity) of staff activities	• Traveler information calls (total, calls per day, calls per route, type of call, average call length, average answer time) • Web site visits by type of information requested • Number of media communications by outlet • Incident response (by type, detection method, level of impact) • Service patrol assists (by shift, type, detection method, route) • Service patrol service times • Number of construction closures
		• Increase system performance and functionality	• General system condition (pavement, bridge) • Number of systems functioning properly • Percent of systems functioning properly
		• Increase customer satisfaction ratings	• Percentage of projects rated good to excellent • Qualitative customer comments
		• Minimize costs	• Average cost for transportation system construction (per lane-mile, VMT, PMT, TMT) • Average cost for transportation system services (per lane-mile, VMT, PMT, TMT) • Cost-benefit measures (best case, midrange, worst case benefits for travel-time savings, traveler information, crash reduction)
		• Maximize revenue	• Toll revenue

Table 3. Minimum Recommended Performance Measures (Shaw 2003).

OPERATIONAL PERFORMANCE	
Quantity of travel (users' perspectives)	• PMT
	• TMT
	• VMT
	• Persons moved
	• Trucks moved
	• Vehicles moved
Quality of travel (users' perspectives)	• Average speed weighted by PMT
	• Average door-to-door travel time
	• Travel time predictability
	• Travel time reliability (% of trips that arrive in acceptable time)
	• Average delay (total, recurring, and incident-based)
	• LOS
Utilization of the system (agency's perspective)	• Percent of system heavily congested (LOS E or F)
	• Density [passenger cars per hour per lane (pcphpl)]
	• Percent of travel heavily congested (LOS E or F)
	• V/C ratio
	• Queuing (frequency and length)
	• Percent of miles operating in desired speed range
	• Vehicle occupancy (persons per vehicle)
	• Duration of congestion (lane-mile-hours at LOS E or F)
Safety	• Incident rate by severity (e.g., fatal, injury) and type (e.g., crash, weather)
Incidents	• Incident induced delay
	• Evacuation clearance time
AGENCY PERFORMANCE	
	• Incident response time by type of incident
	• Toll revenue
	• Bridge condition
	• Pavement condition
	• Percent of ITS equipment operational

- freeway design applications; and
- air quality conformity applications.

In addition to providing a comprehensive list of possible performance metrics, NCHRP (2004) also provides a reduced list of recommended minimum freeway performance metrics (preliminary, see Table 4). More recently, the *Performance Measure Initiative* (NTOC 2005) focused on developing a more manageable list of quality performance measures for use by transportation agencies. Using the results of a literature search and deliberations by the NTOC panel of experts, the following short list of performance measures (see Table 5) is defined for use in internal management, external communication, and comparative measurement.

Table 4. Minimum Recommended Performance Measures (NCHRP 2004).

	PERFORMANCE MEASURE	GEOGRAPHIC SCALE		TIME SCALE					
		Corridor	Area-wide	Peak Hour	Peak Periods	Midday	Night	Daily	Annually
Average Congestion Conditions	Travel time index	✓	✓	✓	✓	✓		✓	
	Total delay (vehicle-hours and person-hours)	✓	✓	✓	✓	✓		✓	
	Bottleneck ("recurring") delay (vehicle-hours)	✓	✓	✓	✓	✓		✓	
	Incident delay (vehicle-hours)	✓	✓	✓	✓	✓		✓	
	Work zone delay (vehicle-hours)	✓	✓	✓	✓	✓		✓	
	Weather delay (vehicle-hours)	✓	✓	✓	✓	✓		✓	
	Delay per person	✓	✓	✓	✓				
	Delay per vehicle	✓	✓	✓	✓				
	Percent of VMT with average speeds < 45 mph	✓	✓	✓	✓				
	Percent of VMT with average speeds < 30 mph	✓	✓	✓	✓				
	Percent of day with average speeds < 45 mph	✓	✓					✓	
	Percent of day with average speeds < 30 mph	✓	✓					✓	
	HOV volumes	✓	✓		✓				
Reliability	Buffer time index	✓	✓	✓	✓	✓		✓	
	95th percentile travel time index								
Incident Management	Detection time	✓	✓		✓				
	Verification time	✓	✓		✓				
	Response time	✓	✓		✓				
	Clearance time	✓	✓		✓				
	On-scene time	✓	✓		✓				
	Total duration	✓	✓		✓				
	No. of incidents by type	✓	✓		✓				
	Reporting by (citizens, police, other agencies) per month	✓	✓		✓				
	Service patrol assists (total and by incident type)	✓	✓		✓				
Work Zones	No. of work zones by type of activity	✓	✓					✓	
	No. of lane-miles lost	✓	✓		✓	✓	✓		
	Lane-mile-hours of work zones	✓	✓		✓	✓	✓		
	Average work zone duration by zone type, lanes lost	✓	✓					✓	
	Average time between rehabilitation activities		✓						
	Average number of days projects completed late		✓						
	Ratio of inactive days to active days		✓						
Weather	Hours affected by (rain, snow, ice, high winds, fog, dust, smoke)	✓	✓					✓	
	Lane-miles affected by (rain, snow, ice, high winds, fog, dust, smoke)	✓	✓					✓	
Operations, General	Service patrol vehicles per mile	✓	✓						✓
	Service patrol vehicles in operation per shift	✓	✓						✓
	Percent freeway miles with [electronic data collection, surveillance cameras, dynamic message signs (DMSs), service patrol coverage]		✓						✓
	Number of messages placed on DMSs	✓	✓						✓
	Individuals receiving traveler information by source (511, other)	✓	✓						✓
	Percent of equipment [DMS, surveillance cameras, sensors, ramp meters, road weather information systems (RWIS)] in good condition	✓	✓						✓
	Percent of total device-days out-of-service (by type of device)	✓	✓						✓
	No. of devices exceeding design life	✓	✓						✓
	Mean time between failures (MTBF) for field equipment (by type of device)	✓	✓						✓
	Customer Satisfaction	Included in surveys of the public for general transportation agency performance							

Table 5. Minimum Recommended Performance Measures (NTOC 2005).

MEASURE		DEFINITION
Customer Satisfaction		Qualitative measure describing customer opinions as very satisfied, somewhat satisfied, neutral, very dissatisfied, and don't know/not applicable.
Extent of Congestion	Spatial	Lane miles of congestion: miles of roadway for which average travel times are 30% longer than unconstrained travel times Percent of congested roadways: 100% × (congested lane miles/total lane miles)
	Temporal	Time during which more than 20% of the roadways are congested (for which average travel times are 30% longer than unconstrained travel times), expressed as hours of congestion
Incident Duration		Median minutes per incident, from notification to clearance
Delay	Non-recurring	Vehicle delays in excess of recurring delay, expressed as vehicle-hours and by time of day, day of week, and day type
	Recurring	Vehicle delays that are repeatable for the current time of day, day of week, and day type, expressed as vehicle-hours
Speed		Average speed of vehicles measured in a single lane, for a single direction at a specific location on the roadway, expressed in miles per hour, feet per second, or kilometers per hour
Throughput	Person	Number of persons, including vehicle occupants, pedestrians, and bicyclists, traversing a roadway section or screen line in one direction per unit time, expressed as persons per hour
	Vehicle	Number of vehicles traversing a roadway section or screen line in one direction per unit time, expressed as vehicles per hour
Travel Time	Link	Average time required to traverse a section of roadway in a single direction, expressed as minutes per trip
	Trip	The average time required to travel from an origin to a destination on a trip that might include multiple modes of travel, expressed as minutes per trip
	Reliability	Buffer index: The additional time that must be added to a trip to ensure that the traveler will arrive at their destination on or before schedule 95% of the time, expressed as minutes, percent of total trip time, or as an index

A general set of performance measures is provided as part of the *ITS Evaluation Resource Guide* (www.its.dot.gov/evaluation/eguide_resource.htm) related to each of the National ITS Program goal areas and intended to evaluate the performance of technology-based systems (see Table 6).

The performance measures identified here address a broader set of transportation facilities, overarching goals and objectives, and subsequent operational activities. It is nonetheless important to have cursory knowledge of typical performance measures in use and those emerging as consistent practice among local, state, and federal transportation agencies to ensure consistency in managed lane facility performance monitoring and evaluation practices.

Table 6. Recommended Performance Measures for Evaluating ITS (FHWA).

GOAL AREA	PERFORMANCE MEASURE
Safety	• Reduction in the overall crash rate
	• Reduction in the rate of crashes resulting in fatalities
	• Reduction in the rate of crashes resulting in injuries
	• Improvement in surrogate measures
Mobility	• Reduction in travel time delay
	• Reduction in travel time variability
	• Improvement in surrogate measures
Capacity/Throughput	• Increase in throughput or effective capacity (maximum rate at which persons or vehicles may traverse a link, node, or network under representative roadway conditions)
Customer Satisfaction	• Difference between users' expectations and experience in relation to a service or product
Productivity	• Cost savings
Energy and Environment	• Reduction in emissions
	• Reduction in fuel consumption

DATA COLLECTION AND PROCESSING

The third step in the performance monitoring and evaluation process, following the identification of goals and objectives and related performance measures, is to collect and process the necessary supporting data. Obviously, a direct relationship exists between the performance measures selected and the data required to support monitoring and evaluation activities.

Neudorff et al. (2003) recommends the following considerations with respect to data collection and processing:

- data to be collected,
- frequency of data collection/schedule,
- data collection locations,
- data collection responsibilities,
- data analysis techniques and responsibilities,
- database management requirements, and
- performance analysis reporting.

General issues related to the data to be collected, data collection methods, data processing and quality control, and data management and archiving are described below. The frequency of, location of, and responsibility for data collection is largely dependent on local conditions and resources and, hence, won't be described further in this report. Data analysis techniques are discussed in the subsequent section, *Monitoring and Evaluation*.

Data to be Collected

NCHRP (2004) suggests three different categories of data for collection:

- facility use and performance data, such as traffic volumes, travel times, and delay;
- staffing and resource allocation and use data, including (1) actions being taken to improve facility operations, (2) working condition of facilities and systems, and (3) use of these control systems and the interaction of the agency with the public; and
- event (e.g., construction activities, other lane closures, and large civic events) and incident data, including location, duration, and nature.

In each of these data categories, it is important to ensure that the available data are not determining the performance measures; instead, the goals and objectives and subsequent related performance measures should fully utilize existing data but seek supplementary data as necessary. In addition, difficult to measure items should not be overlooked (NCHRP 2004).

Data Collection Methods

Based on the same three categories of data, NCHRP (2004) comprehensively describes accompanying data collection methods (see Table 7). Facility use and performance can be monitored and evaluated using data collected (1) continuously across a facility or through special studies and (2) using automatic or manual techniques. Automatic techniques may suffer from reliability problems and questionable accuracy; it is essential to confirm the accuracy of automatically collected data by periodic use of manual devices.

Continuously collected data, irregardless of the method, supports a review of the time-of-day, day-of-week, and geographic trends present in travel patterns. This allows agencies to understand when, where, and how frequently problems are occurring on their roadways and how those trends change as new countermeasures are implemented. Continuous data collection also captures “unusual” conditions; the effect these conditions have on facility performance can be determined and compared against “routine” conditions. This allows agencies to understand the relative importance of different “unusual” events and gage the relative value of spending resources on responding more effectively to these events versus spending those resources on improving “routine” conditions (NCHRP 2004).

Where continuous data systems do not exist and agencies cannot afford to implement them (or where supplemental data sets are required), special, short-duration studies are often

Table 7. General Data Collection Methods (NCHRP 2004).

DATA	METHOD
Facility Use and Performance	
Continuous Data Collection	• Point Detection. Surveillance equipment (i.e., inductance loops, microwave radar, video detection, etc.) placed at specific locations along a roadway report data on vehicle volume and lane occupancy (which can subsequently be used to estimate vehicle speed and travel time), or, when deployed in a "dual loop" configuration, can directly measure and report vehicle speed and vehicle classification (by length). Point detectors provide information about a single location; that location may not accurately represent the performance of the rest of the roadway segment with which those data are associated.
	• Beacon-based Probe Vehicle Data. A device (beacon) that uses Dedicated Short-Range Communication (DSRC) standards interrogates electronic vehicle tags as vehicles pass that reader location. By matching the time and location data associated with each vehicle as it passes from one beacon location to the next, it is possible to determine travel time, delay, and trip reliability measures. Travel times are more accurate than those estimated from point detectors, but the geographic distribution of delays and the measure of total facility use are not provided; vehicle volumes must be collected from other sources.
	• Non-traditional Probe Vehicle Performance. General approaches rely on cell phone tracking and Global Positioning System (GPS)-equipped vehicles with wireless data transmission to determine vehicle location and speeds. None of these systems are actively used in the U.S. Like beacon-based probe vehicle data, vehicle volumes must be collected from other sources.
Special Study Data Collection	• Traffic volumes using trailer-mounted non-intrusive data collection technologies (i.e., microwave radar, video, or acoustic sensor technologies) or conventional road tube-based counters on all ramps within a corridor to estimate volumes on the freeway mainline.
	• Travel time and delay using floating car studies or various license plate (or other vehicle) matching techniques.
	• Other congestion measures, including the geographic extent of congestion, using aerial surveillance.
	• Vehicle occupancy counts are done manually, although some vendors of image detection software are starting to market systems that they claim can count passengers in vehicles.
Staffing and Resource Allocation and Use	
	• Newer, more automated control systems often record many of these key statistics automatically and produce reports used by traffic management personnel to prioritize work. Where these data are not collected automatically, minor changes to personnel work tasks and/or data processing systems are usually required to capture the work load and other resource usage information that allows analysis control system functioning and management of personnel and equipment resources.
Event and Incident Data	
	• In almost all cases, data collection related to incidents and special events requires manual entry of data. The key is to perform this entry as few times as possible and share the data across organizations and applications as much as possible.
	• Computer Aided Dispatch (CAD) systems can be a source of incident data, since the communication records with officers indicate when notification of an incident takes place, when requests for additional resources are made, and when the incident is cleared and the officer is back on patrol.
	• Some traffic management centers have their operators record key incident and event statistics.

performed. These special studies have the advantage of generally having lower costs. They have the disadvantage of (normally) being non-continuous and are thus less likely to be able to accurately collect performance data on the number, frequency, and severity of “unusual” events. In addition, special studies generally focus on collecting specific pieces of information (i.e., vehicle occupancy and transit ridership information) not available through existing sources (NCHRP 2004).

To capture motorist perception data, the *ITS Evaluation Resource Guide* (www.its.dot.gov/evaluation/eguide_resource.htm) recommends the use of focus groups, stated preference surveys, or revealed preference surveys. Focus groups enable deeper exploration of user perceptions, values, and behavior but have no statistical significance and should not be extrapolated in order to make generalizations about the larger population. Stated preference surveys provide a basis from which to predict how different types of users will behave under various conditions. Stated preference survey results are not suitable for an objective assessment of measures such as actual amount of time saved or miles traveled. For these measures, revealed preference survey techniques, in which the user is observed and his or her actions are recorded, should be used. Revealed preference surveys provide an objective measure of traveler behavior but cannot provide explanations or motivations for user actions.

Tempering these general guidelines with national practice, Shaw (2003) summarized reported data collection techniques by data type (see Table 8). These methods represent the most commonly reported, not all of the possible data collection techniques. When selecting data collection methods, researchers should consider the cost and accuracy of each method, the availability of local resources to implement each method, the ease of implementation, and the ultimate data analysis requirements.

Data Processing and Quality Control

As part of the *Performance Measure Initiative*, NTOC (2005) defined specific processing guidelines for each of their 10 recommended minimum performance measures (see Table 9).

In many instances, performance monitoring and evaluation requires integrating two or more disparate databases to form a single unified database. Commonly, traffic performance data are integrated with events that affect traffic performance such as operational actions (i.e., incident management, ramp metering, etc.), weather, work zones, and special events.

Table 8. Commonly Reported Data Collection Methods (Shaw 2003).

CUSTOMER SURVEYS	
• Customer satisfaction	• Satisfaction with traveler information
• Incident response times	• Satisfaction with HOV lanes
• Satisfaction with maintenance/ construction zones	• Satisfaction with ramp meters
	• Satisfaction with service patrols
TRAVEL SURVEYS	
• Origin-destination	• Travel predictability
• Number of daily trips and purpose	• Congestion tolerance
• Trip-based travel time	
INDUCTIVE LOOPS	
• Traffic volumes and classification	• Speed
• Density (using vehicle occupancy)	• Lane occupancy
OTHER NON-INTRUSIVE VEHICLE DETECTORS (hoses/tubes, radar, acoustic, video, and seismic technologies)	
• Traffic volumes and classification	• Speed
• Density	• Lane occupancy
VIDEO SURVEILLANCE (not video detection)	
• Incident detection	
PROBE VEHICLES (transponders, license plate surveys, and GPS)	
• Travel times	• Speeds
MODELING/ESTIMATION	
• Capacity	• Travel times
• LOS	• Speed
• VMT	• Benefits
• Evacuation clearance time	• Queuing
• Percent system congested	• Delay
• Percent travel congested	• V/C ratio
• Duration of congestion	

To merge these data sources, three (or more) variables are commonly used: date, time, and location. Because location referencing is often the complicating factor, many suggest that the use of geographic information systems (GIS) provides the ideal platform for data fusion and subsequent data analysis (NCHRP 2004).

With respect to the quality of data to support determination of performance measures, continuous data quality has been influenced by two prevailing issues: (1) the difficulty of maintaining extensive electronic field equipment (sensors and communication) and (2) different data quality requirements for real-time operations and historical uses of continuous data. Data quality problems can be traced primarily to two sources: (1) improper installation (including initial calibration and acceptance testing of equipment) and (2) inadequate detector maintenance

Table 9. Data Processing Requriements for Key Performance Measures (NTOC 2005).

MEASURE		DATA PROCESSING
Customer Satisfaction		Provide both the distribution of answers (i.e., percent answering very satisfied, somewhat satisfied, etc.) as well as average response by travel location and type of customer.
Extent of Congestion	Spatial	1. Segment roadways into sections. 2. Select time period; unconstrained travel times must be constant. 3. Calculate unconstrained travel times for the time period of interest for each section. 4. Determine average travel times for the time period of interest for each section. 5. Measure length of each section for which this calculation is made. 6. Sum the lengths of the roadway sections for which travel times are 30% greater than the unconstrained travel time. 7. Sum of congested roadway sections (Step 5)/total lengths of all roadway sections.
	Temporal	1. Select time period (may be 24 hours). 2. Divide time period into 5-minute intervals. 3. Execute Steps 1 through 5 of the Extent of Congestion-Spatial performance measure. 4. Identify congested sections with actual travel times >30% greater than unconstrained travel times. 5. Count time periods for which >20% of the sections are identified as congested. 6. Calculate number of congested time periods × 5 (min/measurement)/60 min/hr.
Incident Duration		Calculate difference between notification and removal by roadway and time of day.
Delay	Non-recurring	1. Select roadways on which delay is to be measured. 2. Select time periods during which delay is to be measured. 3. Determine the vehicle demand on the roadway during the selected time period. 4. Measure delay during the selected time period. 5. Calculate delay × demand. 6. Calculate delay for the measurement period – recurring delay for the same roadway segment, time-of-day, and day-type.
	Recurring	1. Select roadways on which delay is to be measured. 2. Select time periods during which delay is to be measured. 3. Determine the vehicle demand on the roadway during the selected time period. 4. Measure delay during the selected time period during normal conditions (i.e., when there are no incidents or special events). 5. Calculate delay × demand.
Speed		Sum of individual vehicle speeds/number of vehicles
Throughput	Person	Sum of persons per hour carried on all modes traversing the roadway or screen line.
	Vehicle	Sum of all vehicles per hour traversing the roadway or screen line.
Travel Time	Link	Sum of travel times (floating car)/number of trips.
	Trip	Travel time for each mode used during the trip, including walking times and wait times from origin to destination. Sum of travel times/number of trips.
	Reliability	1. Multiple measurements of travel time for a given time of day and day of week, for which repeatable traffic and roadway conditions exist. 2. Travel times arranged in ascending order. 3. Sum of the trip durations/number of trips. 4. Top (longest) 5% of trips is eliminated, leaving a truncated travel time list. 5. Buffer time = longest travel time of the truncated distribution – average travel time. 6. To express buffer time as a percent, divide buffer index by average (Step 3).

due to funding shortfalls. NCHRP (2004) recommends the following strategies for continuous data processing and quality control:

- improve data quality at the source if possible (i.e., improve maintenance and calibration of traffic sensors),
- apply quality checks to automate identification of invalid data,
- use various levels of metadata to document how data have been transformed, and
- make data quality results available to data and information consumers.

For non-continuously collected data (i.e., sample-based data), data collected during certain daily time periods, weekdays, or months are used to represent a daily, monthly, or annual average or data collected at certain locations or on certain types of facilities are used to represent all facilities in a region. Obtaining adequate samples and addressing sample bias should be addressed when computing summary statistics.

Data Management and Archiving

To monitor long-term changes in a transportation facility, real-time data must be maintained and reused. More specifically, Neudorff et al. (2003) recommends data archiving to provide more and better information in managing and operating the system, maximize the effectiveness of the data collection infrastructure, reduce the need for and subsequent costs of manual data collection, and establish good business practices for managing and operating the transportation system similar to other industries.

MONITORING AND EVALUATION

Monitoring and evaluation steps involve periodic analysis of appropriate data, comparing observed performance results with previously observed performance and established performance targets. This repetitive process allows practitioners to assess the effectiveness of their efforts, identify areas for improvement, justify these improvements, demonstrate benefits provided by the program, and support requests for additional resources. Evaluation must occur throughout the life cycle of the system and the associated facility.

Following data collection, quantitative measures may be processed into average values for each level of stratification used or reported simultaneously with their standard deviations, with comparisons calculated as ratios of standard deviations. If a comparison of two time periods is involved, the percentage change from the earlier to the later period might be calculated. Some qualitative measures, obtained through surveys, may be presented to yield frequency distributions for the response categories (FTA 2002). Monitoring and evaluation may also involve the use of statistical inference techniques. If the data are based on a <100 percent data collection effort (i.e., sampling), exact values of the statistics cannot be calculated. Data based on samples can be expressed as two-sided confidence intervals (i.e., $\alpha = 0.05$).

A number of more comprehensive and robust analysis tools are also available to support facility monitoring and evaluation. *Decision Support Methodology for Selecting Traffic Analysis Tools* (FHWA 2003) identifies the following general analysis methods used in the performance monitoring and evaluation process:

- *Capacity Analysis*. HCM (2000) provides methodologies for determining the performance and LOS of a facility but, as mentioned previously, predicts only average conditions over a fixed time period and cannot detect minor changes in facility performance.
- *Simulation*. Simulation is able to estimate changes in performance (e.g., average speeds, travel time, delays, and emissions) undetected by HCM methods but requires significant input data (i.e., characteristics of each link, link traffic flow information, and others) and calibration to actual conditions in the field.
- *Before and After Studies*. Before and after studies document observed performance prior to and following an improvement but are challenged by confounding factors in the environment of study, driver adjustment periods, temporal changes, and random fluctuations in events (i.e., crash data).
- *Alternatives Analysis*. Benefit-cost comparisons (the most widely accepted alternatives analysis methodology) are possible when the benefits of an improvement are quantifiable and can be assigned a monetary value and costs are inclusive of capital costs and continuing costs (i.e., maintenance costs, equipment replacement, staffing costs to operate the system, utilities costs, etc.).

The first two analysis methods – capacity analysis and simulation – are appropriate for ongoing system monitoring, while the latter two analysis methods – before and after and alternatives analysis – are more appropriate for evaluation prior to or following implementation.

FHWA (2003) recommends consideration of the following capabilities when selecting a method of analysis. In brief, the selected analysis method should be able to:

- accommodate the analysis context (i.e., planning, design, or operations/construction);
- accommodate the appropriate geographic scope or study area (i.e., isolated intersection, single roadway, corridor, or network);
- model various facility types (i.e., freeways, arterials, HOV lanes, ramps, etc.);
- analyze various travel modes [i.e., single occupancy vehicle (SOV), HOV, bus, bicycle, pedestrian, etc.];
- analyze various traffic management strategies and applications (i.e., ramp metering, signal coordination, incident management, etc.);
- estimate traveler responses to traffic management strategies (i.e., route diversion, departure time, mode shift, destination choice, induced/foregone demand, etc.);
- directly produce performance measures (i.e., crashes, fatalities, throughput, volumes, VMT, travel time, speed, VHT, cost savings, emissions, fuel consumption, noise, etc.); and
- be cost effective (i.e., capital cost, level of effort, ease of use, hardware requirements, data requirements, animation, etc.).

The frequency of analysis is variable and highly dependent upon the amount of variation observed for a particular facility. Dynamic performance measures such as violation rates should be collected on a monthly basis when the facility is first implemented and then annually after 1 to 2 years of operation. Continuously collected data (i.e., vehicle volumes, classification, speeds, etc.) can be analyzed monthly, quarterly, or annually. These continuous counts should be compared with supplemental manual vehicle occupancy and travel time studies at a minimum quarterly frequency initially, with lower frequency of analysis (i.e., annually) as facility operations stabilize. Analysis of performance measures that have infrequent occurrences (i.e., accidents) or require considerable data collection resources (i.e., customer satisfaction surveys) can be conducted annually or every 2 to 3 years (Turnbull et al. 1991).

REPORTING

Communicating results of performance is an important element of the overall monitoring and evaluation process. According to Shaw (2003), typical performance reporting occurs on an annual basis and as part of a larger transportation plan document. National practice relies upon a combination of written text (9 percent), tables (37 percent), charts (24 percent), and maps (24 percent) to report on facility performance. These aggregate results reflect only a limited application of performance reporting. NCHRP (2004) describes a much broader set of applications appropriate for national, state, and local levels and ranging from real-time to long-term reporting:

- real-time web sites providing specific traveler information (i.e., incidents, etc.);
- operations planning reports supporting daily road or transit operations;
- annual, monthly, and quarterly reports summarizing regional or statewide conditions, recent performance, and trends;
- before and after and issue studies focusing on corridors, times of day, or specific problems (i.e., travel time variations or freight movement);
- project analysis reports, used to support public transportation, operational, or demand management programs, describing total system effects; and
- long-range planning reports providing trend information and travel forecasts, along with more typical planning measures.

The audience for these applications is broad, but in general can be divided into technical and non-technical groups, defined by information needs, time, and locations or categorized by jurisdictional levels:

- local, requiring real-time information to select and implement operational plans, provide traveler information, and plan future improvements;
- regional, requiring aggregated real-time information to address the performance of the system and implement and monitor regional response plans;
- state, requiring information specific enough to distinguish modal performance for resource allocation and programming and long-range planning; and
- national, requiring long-term, aggregate information to determine net effect of strategies, support policy making and goal setting, develop/justify legislation, and develop reports for Congress (Neudorff et al. 2003).

While the content and detail of reports to these groups may differ, collectively they document accomplishments, communicate the benefits of the transportation program, establish management accountability for results, and provide a point of departure for discussion of future revisions to policy goals and objectives, performance targets, or setting performance measures themselves (Neudorff et al. 2003).

CHAPTER 4:
GUIDELINES AND PRACTICES FOR MANAGED LANE FACILITY PERFORMANCE MONITORING AND EVALUATION

For each of the six general types of managed lane strategies considered as part of this investigation – HOV, value-priced, and HOT lanes, exclusive lanes, mixed-flow separation/bypass lanes, lane restrictions, and dual facilities – pertinent findings resulting from a review of collective guidelines and site-specific evaluations is provided. While significant national-level guidance documents were available for overall freeway performance monitoring and evaluation, information specific to managed lane facilities was largely limited to site-specific evaluation studies. Further, much of the information considered managed lane facilities currently in operation (i.e., HOV lanes and truck lane restrictions) or in operation as a demonstration project, although a number of studies were uncovered that considered the feasibility of various managed lane facilities prior to implementation (i.e., valued-priced and HOT lanes and exclusive bus and truck lanes).

HIGH-OCCUPANCY VEHICLE LANES

Collective Guidelines

Researchers uncovered few documents, overall, that provided collective guidelines for managed lane facility performance and monitoring. Not surprisingly, the majority of these documents on HOV lane facilities; HOV lane facilities experienced early and widespread implementation and, hence, have been the subject of significant study. Key documents include the following: (1) *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities* (Turnbull et al. 1991) and (2) *High-occupancy Vehicle Monitoring and Evaluation Framework* (Bracewell et al. 1999). [Gan et al. (2002) developed operational performance models for freeway HOV lanes using CORSIM 5.0, but this document provided little additional guidance related to the evaluation and monitoring process.]

In the first document, Turnbull et al. (1991) reviewed a sampling of HOV facility evaluation studies that included the following:

- Shirley Highway in Northern Virginia;
- San Bernardino Freeway in Los Angeles, California;

- Houston, Texas;
- I-5 in Seattle, Washington;
- I-394 in Minneapolis, Minnesota;
- Route 55 in Orange County, California;
- Santa Clara County, California; and
- I-95 in Fort Lee, New Jersey.

Specific results from these studies formed the basis of general recommendations related to evaluating the performance and effectiveness of HOV lane facilities. In particular, Turnbull et al. (1991) defined common goals and objectives, accompanying performance measures, typical target values or thresholds for each performance measure, and attendant data requirements (see Table 10). Note that the recommendations provided here are relatively consistent with more recent general guidelines for performance monitoring and evaluation (i.e., a focus on travel time rather than or in addition to level of service, etc.).

Challenging the development of these guidelines were the lack of (1) ongoing monitoring efforts (as compared to initial evaluations); (2) clearly defined, measurable goals and objectives; (3) consensus on performance measures and data collection/evaluation methods; (4) quantitative benchmarks against which performance can be measured; (5) statistically valid, comprehensive evaluation methods that consider the full range of impacts, including confounding effects (i.e., change in gasoline prices); and (6) quality data (Turnbull et al. 1991).

More recently, Bracewell et al. (1999) developed a recommended framework for monitoring and evaluating the performance of the arterials and freeway HOV lanes in Vancouver, British Columbia. Citing the findings of the Turnbull et al. (1991) study, as well as more recent site-specific evaluations conducted for the Seattle-area HOV lane system and the I-394 HOV lanes in Minneapolis, Minnesota, Bracewell et al. (1999) reported similar variability in HOV lane performance monitoring approaches but identified four "core" objectives for performance: (1) people-moving efficiency, (2) travel-time savings, (3) safety, and (4) compliance categorized as primary, supporting, and operational (see Table 11). General companion performance measures and supporting data requirements were also provided. With respect to evaluation and monitoring, investigators suggested that the frequency of periodic evaluations (i.e., monitoring) should be higher in the first few years of HOV lane operation; once stabilized, performance monitoring activities can be performed less frequently. HOV lane

Table 10. Suggested Goals and Objectives, Performance Measures, Target Values/Thresholds and Data Requirements for HOV Facilities (Turnbull et al. 1991).

GOALS/OBJECTIVES	PERFORMANCE MEASURES	TARGET VALUES/ THRESHOLDS	DATA REQUIREMENTS
The HOV facility should improve the capability of a congested freeway corridor to move more people by increasing the number of persons per vehicle.	• Actual and percent increase in the person movement efficiency • Actual and percent increase in average vehicle occupancy rate • Actual and percent increase in carpools and vanpools • Actual and percent increase in bus riders	• >10% increase in the peak-hour, peak-direction average vehicle occupancy • Person volume increase > the directional lanes increase • >20% increase in carpoolers • 10%–20% increase in bus riders	Primary • Before-and-after vehicle and vehicle occupancy counts on the HOV lane(s), adjacent freeway, and control freeway Secondary • Before-and-after vehicle and occupancy counts on parallel roadways • After surveys of users of the HOV facility users and non-users
The HOV facility should increase the operating efficiency of bus service in the freeway corridor.	• Improvement in vehicle productivity (operating cost per vehicle-mile, operating cost per passenger, operating cost per passenger mile) • Improved bus schedule adherence (on-time performance) • Improved bus safety (accident rates)	• 5%–20% improvement in vehicle productivity and operating cost per vehicle-mile, per passenger, and per passenger mile • >95%+ on-time schedule adherence	Before-and-after • Bus service levels • Vehicle productivity • On-time performance • Number and severity of bus accidents • Vehicle operating costs • Changes in labor, fuel, and other costs • On-board ridership surveys
The HOV facility should provide travel-time savings and a more reliable trip time to HOVs utilizing the HOV facility.	• Peak-period, peak-direction travel time in the HOV lane(s) should be less than the travel time in adjacent freeway lanes • Increase in travel time reliability for vehicles using HOV lane(s)	• 1 minute per HOV facility mile of travel-time savings • >5–7 minute peak hour travel-time savings	Before • General purpose lane travel times After • General purpose and HOV lane travel times
The HOV facility should have favorable impacts on air quality and energy consumption.	• Reduction in emissions • Reduction in total fuel consumption • Reduction in the growth of VMT and VHT	• HOV lane(s) should have a more positive impact than would either no improvement or the addition of a mixed traffic lane • More specific levels can be defined based on demand estimation results	Estimations based on • Vehicle and occupancy counts • Travel time runs • Survey responses

Table 10. Suggested Goals and Objectives, Performance Measures, Target Values/Thresholds and Data Requirements for HOV Facilities (Continued, Turnbull et al. 1991).

GOALS/OBJECTIVES	PERFORMANCE MEASURES	TARGET VALUES/ THRESHOLDS	DATA REQUIREMENTS
The HOV facility should increase the per lane efficiency of the total freeway facility.	• Improvement in the peak-hour per lane efficiency of the total facility	• 5%–20% increase in the peak-hour per lane efficiency of the total facility	• Before-and-after vehicle and vehicle occupancy counts on the HOV lane(s) and general-purpose lanes
The HOV facility should not unduly impact the operation of the freeway mainlanes.	• The level of service in the freeway mainlanes should not decline		• Before-and-after vehicle and vehicle occupancy counts on the HOV lane(s) and general-purpose lanes
The HOV facility should be safe and should not unduly impact the safety of the freeway general purpose mainlanes.	• Number and severity of accidents for HOV and freeway lanes • Accident rate per million vehicle miles of travel • Accident rate per million passenger miles of travel	• More specific levels can be defined based on local traffic, accident, and geometric characteristics	Before • Number, type, and severity of accidents on the general-purpose lanes After • Number, type, and severity of accidents on the HOV and general-purpose lanes
The HOV facility should have public support.	• Support for the facility among users, non-users, general public, and policy makers • Violation rates (percent of vehicles not meeting the occupancy requirement)	• A majority of users and non-users should feel the HOV facility is a good transportation improvement • <10% violation rates for exclusive and contraflow lanes and <20% violation rates for concurrent flow lanes	• Surveys of users, non-users, focus groups, and the general public • Monitoring of calls and letters, newspaper articles • Other public reactions relating to the facility • Violation rates • Enforcement levels
The HOV facility should be a cost-effective transportation improvement.	• Benefit-cost ratio	• Benefit/cost ratio (B/C) > 1	• Total cost (capital and operating) of the project • Benefits, with travel-time savings to persons using the HOV facility as a primary benefit

Table 11. Suggested Goals and Objectives, Performance Measures, and Data Requirements for HOV Facilities (Bracewell et al. 1999).

OBJECTIVE		MEASURE	DEFINITION	DATA
Primary	Person Throughput	Per-Lane Efficiency	Average speed × persons by lane and per unit time	• Travel time surveys • Vehicle classification and occupancy counts • Traffic volumes
		Average Vehicle Occupancy	Total vehicle occupants/total vehicles	• Vehicle classification and occupancy counts • Traffic volumes
		HOV Market Share	Total persons using HOV lane/total passenger trips	• Traffic volumes • Average vehicle occupancy
Supporting	Travel Time Savings	Travel Time Difference	General purpose (GP) – HOV travel times	• Travel time surveys
	Travel Time Reliability	Travel Speed Standard Deviation	HOV and GP travel time standard deviations	• Travel time surveys
	Public Support	Support for HOV Lanes	Percent of HOV users and non-users expressing support	• Public opinion survey
Operational	Compliance	Compliance Rate	Compliant vehicles in HOV lane/total vehicles in HOV lane	• Compliance data • Traffic volumes
	Safety	Accident Rate	Accidents/million-vehicles miles of travel	• Accident statistics • Traffic volumes
	GP Lane Impact	GP Lane Travel Speed		• Travel time surveys

evaluations should be conducted at the same time each year to avoid any seasonal confounding effects on performance. Researches later applied the recommendations comprising this framework document to an HOV facility along the Barnet/Hastings corridor (Barnet Highway) to test its validity; the specific results of this effort are described below under *Site-specific Findings*.

Site-specific Findings

A number of site-specific evaluation studies conducted in Northern Virginia, California, Texas, Washington, Minnesota, and New Jersey were previously considered by Turnbull et al. (1991), culminating in the *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities*. Building upon this earlier work, Bracewell et al. (1999) supplemented these suggested procedures with more recent site-specific evaluations conducted in Washington and Minnesota to develop a *High-Occupancy Vehicle Monitoring and Evaluation Framework*.

To avoid duplicating these efforts, this investigation considers only those site-specific findings that are more recent than those reported by either Turnbull et al. (1991) or Bracewell et al. (1999) and/or have not been integrated into recommended practice. These efforts include the following:

- various facilities in North America (Wellander and Leotta 2000);
- I-93 Expressway in Boston, Massachusetts (Casey 2000);
- Long Island Expressway in Long Island, New York (O'Connell et al. 2000);
- various facilities in Texas (Stockton et al. 2000, Daniels and Stockton 2002);
- I-15 in Salt Lake City, Utah (Martin et al. 2002);
- various facilities in Seattle, Washington (Hallenbeck et al. 2004); and
- various facilities in Atlanta, Georgia (unpublished).

Various Facilities, North America

Without implicitly recommending practices or procedures for HOV lane performance monitoring and evaluation, Wellander and Leotta (2000) summarized the effectiveness of various HOV facilities across North America located in Washington D.C., Texas, Oregon, Washington, Vancouver, B.C., New Jersey, and Massachusetts. In doing so, the authors provide useful information related to various goals and objectives, performance measures, and target values/thresholds observed in national practice (see Table 12).

Wellander and Leotta (2000) state that an effective HOV lane is one that (1) carries more people per lane than adjacent GP lanes do during the most congested periods of the day, (2) experiences higher speeds than adjacent GP lanes during the most congested periods of the day, and (3) can be appropriately managed and enforced. Secondary objectives identified by the authors include modal shifts to HOVs, air quality improvements, traffic congestion relief, and more reliable travel times for users. The authors also make an important distinction between congestion *reduction* and congestion *management*; HOV lanes are intended to increase the number of people rather than the number of vehicles being carried on a roadway, thereby increasing mobility. A primary advantage of HOV lanes is that they enable eligible vehicles to bypass roadway congestion (i.e., congestion management).

Turning attention to related performance measures, the most significant measure of HOV lane performance is person-movement; HOV lanes may be considered effective if they are carrying more people than adjacent GP traffic lanes. As an indicator of whether an HOV lane is meeting this objective, Wellander and Leotta (2000) developed an HOV person- throughput effectiveness index; if this index is greater than 1.0, then the HOV lane is carrying more people per lane than the adjacent GP lanes on average. Across all facilities for which adequate data

Table 12. Observed Performance Measures for HOV Lane Facilities in North America (Wellander and Leotta 2000).

	WASHINGTON D.C.						TEXAS						PORTLAND, OR	SEATTLE, WA					VANCOUVER, B.C.	NEW JERSEY	BOSTON, MA
	I-395	I-95	I-66 exclusive	I-66 contraflow	I-270 east leg	I-270 west leg	Katy	U.S. 290	I-30	I-45 N	U.S. 59 S	I-45	I-5 N	I-5 N	SR 520	I-405 north leg	I-405 south leg	I-90	Barnet Highway	I-80	SE Expressway
Facility Characteristics																					
Occupancy Requirement	3+	3+	2+	2+	2+	2+	2 or 3+	2+	2+	2+	2+	2+	2+	2+	3+	2+	2+	2+	2+	No longer in operation	2+
Facility Length	9–27 mi.						5.2–13.5 mi.						3.5 mi.	1.4–14.2 mi.					4.8 mi.	10.6 mi.	5.5 mi.
Person Throughput																					
Persons Carried in HOV Lane, Peak Hour	a.m.		1,100–4,700 (avg. 2,550)				a.m.	2,155–4,950					2,250–2,360	2,150–5,250 (avg. 3,500)					N/A	1,950–2,170 (estimated)	N/A
	p.m.		1,600–4,500 (avg. 2,733)																		
HOV Person Throughput Effectiveness Index	a.m.		0.79–1.63 (avg. 1.22)				N/A						1.20–1.35 (avg. 1.29)	1.05–1.74 (avg. 1.41)					N/A	N/A	N/A
	p.m.		0.82–1.75 (avg. 1.24)																		
Lane Utilization																					
HOV Lane Utilization (vphpl)	a.m.		663–1,713				a.m.	799–1,429						190–1,550 (peak period, direction)					a.m. 723	a.m. 780	a.m. 949
	p.m.		615–1,671										p.m. 800–900						p.m. 508	p.m. 835	
Travel Time Savings																					
Minutes per Mile	a.m.		0.6–1.5				1.2–2.1						1.4–1.7	0.1–2.9					0.9–1.4	0.3	a.m. 1.4
	p.m.		0.6–1.3																		p.m. 2.5
Total Minutes Saved	a.m.		5–41				a.m.	6–28					5–6	1–13					4–7	3 (average)	a.m. 7
	p.m.		9–34																		p.m. 14

were available from which this measure could be calculated, the index ranged from 0.79 to 1.75. Of the 20 cases, 4 in the Washington, D.C., area were less than 1.00. In total, however, 80 percent of the cases assessed were proportionately carrying more people in the HOV lane than in the adjacent GP lanes. For each of the three urban areas for which this measure was calculated, the average index was greater than 1.0, ranging from 1.22 to 1.41, indicating that on average the facilities are effective with respect to this measure.

The most effective facilities were those with a relatively high percentage of transit usage. In Washington, the SR 520 westbound shoulder HOV lane carries 34 percent of the a.m. peak-hour corridor persons in only 5 percent of the corridor vehicles. This lane has a 3+ occupancy requirement, and transit vehicles represent nearly one-half of all HOV lane vehicles. In Portland, Oregon, a recently opened HOV lane carries 40 percent of the total p.m. peak-hour persons moved in the corridor, with counts of 2,360 persons in the HOV lane as compared to an average of 1,780 persons in each of the adjacent GP lanes. Since implementation of the HOV lane, peak-hour corridor person-throughput has increased by 11 percent. Even if an HOV lane is experiencing a person-throughput index of less than 1.0, that facility is not necessarily considered to be a failure. Other factors need to be taken into consideration; the facility may be providing a level of travel time reliability critical to the success of regional transit operations or the facility may be located in an area that is expected to experience significant growth and associated traffic congestion.

Utilization of an HOV lane refers to the number of vehicles using the lane and is a function of eligibility requirements, the number of eligible vehicles using a facility, how the HOV lane is separated from GP lanes (e.g., physical barrier or paint stripe), and the traffic conditions of GP lanes. For the facilities reviewed, the HOV lane utilization during peak hours varied from 190 to 1,713 vehicles per hour per lane (vphpl), with an average peak-hour utilization of 1,100 vphpl.

Comparatively, the *HOV Systems Manual* (1998) indicates a minimum threshold of 400 to 800 vphpl and a maximum threshold of 1,200 to 1,500 vphpl for concurrent-flow freeway HOV lanes and a minimum threshold of 200 to 400 vphpl and a maximum threshold of 800 to 1,000 vphpl for a bus-only facility in its own right-of-way. Of total HOV facilities reviewed, about 95, 75, and 45 percent carried more than 600, 800, and 1,200 vphpl, respectively, during the peak hour (Wellander and Leotta 2000).

The *HOV Systems Manual* (*1998*) also suggests that HOV lanes should provide a minimum of 1 minute per mile in travel-time savings and an overall travel-time savings of at least 5 minutes; an overall travel-time savings of 8 minutes is desirable. Of the facilities reviewed, 50 percent experienced travel-time savings of 1 minute or more per mile; 70 percent experienced overall travel-time savings of at least 5 minutes, and 40 percent showed savings of 8+ minutes.

Few data regarding changes in mode choice were available on the facilities evaluated as part of this review. In a survey conducted in Texas, 35 to 66 percent of carpoolers and 25 to 46 percent of HOV lane bus riders reported driving alone before the HOV lane opened. On average, an estimated 36 percent of the current bus ridership in Texas is due to construction of HOV lanes. In Portland, Oregon, transit ridership for the HOV lane corridor increased by 4 to 6 percent after implementation of the HOV lane. After implementation of the HOV lane in Vancouver, British Columbia, 2+ HOVs increased from 19 to 32 percent in the a.m. peak and from 20 to 25 percent in the p.m. peak. Average vehicle occupancy increased from 1.22 to 1.35 in the a.m. peak and from 1.25 to 1.28 in the p.m. peak.

Data related to air quality effects of HOV lanes were also limited for the facilities reviewed. In Texas, modeling analysis conducted on the Katy Freeway compared "do nothing," "new HOV lane," and "new GP lane" alternatives. Simulation results indicated generally that the "new HOV lane" alternative performed better for hydrocarbons and carbon monoxide but had similar results to "new GP lane" for nitrous oxide.

Though difficult to compare because of variable content and format, Wellander and Leotta (2000) observed consistency in public support for HOV lanes in their review of recently conducted public surveys:

Seattle, Washington

- 94 and 74 percent of HOV and SOV users, respectively, think "HOV lanes are a good idea;"
- 85 and 58 percent of HOV and SOV users do not think "HOV lanes should be open to all traffic;" and
- 82 and 59 percent of HOV and SOV users also do not think "constructing HOV lanes is unfair to taxpayers who choose to drive alone."

Portland, Oregon

- 76.9 percent favored the HOV lane trial;
- 70 percent believed HOV lanes were either a "good" or an "excellent" idea; and
- 62.5 percent believed the corridor commute will benefit because of the HOV lane.

Texas (three HOV lane corridors)

- "Are HOV lanes good transportation improvements?" 65 to 66 percent of GP lane users said "yes;"
- "Are the HOV lanes sufficiently utilized?" 19 to 48 percent of GP lane users, 62 to 64 percent of bus riders, and 83 to 95 percent of car/vanpoolers indicated "yes."

British Columbia

While the Barnet Highway HOV lane facility was mentioned briefly by Wellander and Leotta (2000), additional findings applying Bracewell et al.'s (1999) framework for HOV lane monitoring and evaluation are briefly summarized in Table 13 for comparison.

Table 13. Goals and Objectives, Performance Measures, and Results for the Barnet Highway HOV Facility (Bracewell et al. 1999).

OBJECTIVE		MEASURE	RESULTS			
			EB Barnet Highway		WB Barnet Highway	
			Before HOV	After HOV	Before HOV	After HOV
Primary	Person Throughput	Per-Lane Efficiency	72	98	83	92
		Average Vehicle Occupancy[1]	1.32	1.35	1.25	1.28
		HOV Market Share[1]	52	53	48	51
Supporting	Travel Time Savings	Travel Time Difference[1]		2.8		8.1
	Travel Time Reliability	Travel Speed Standard Deviation[1]		HOV 3.9 GP 5.1		HOV 3.0 GP 5.2
	Public Support	Support for HOV Lanes	N/A	N/A	N/A	N/A
Operational	Compliance	Compliance Rate		85		80
	Safety	Accident Rate	N/A	N/A	N/A	N/A
	Impact on GP Lanes	GP Travel Speed[1]		+6.84 mph		+3.72 mph

[1] Reflects results corridor-wide which includes 6.21 miles of arterial HOV facilities and 4.97 miles of freeway facilities.

Massachusetts

With a focus on improving air quality, the Massachusetts Highway Department (MassHighway) operates two HOV lanes: (1) I-93 North is a southbound concurrent flow lane approximately 2 miles in length and (2) I-93 South (Southeast Expressway) is a contraflow lane 6 miles in length. Both operate during peak travel periods with a current occupancy requirement of 2+ passengers per vehicle. Both HOV lanes are physically separated from the general-purpose lanes, by a raised permanent median along I-93 North and by a movable barrier along the Southeast Expressway.

The HOV lanes as they exist today are a result of the Massachusetts Air Pollution 146 Regulation 310 CMR 7.37 that requires performance and air quality monitoring and related standards that must be met: (1) a minimum of LOS C in the HOV lane; (2) average HOV trip times that are at least 1 minute per mile less than average trip times on adjacent general purpose traffic lanes during peak hours of travel; and (3) "greater improvement in air quality for volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx)…in the long and short term."

Key findings reported by Casey (2000) for the performance of the HOV lanes are summarized in Tables 14 and 15. Note that despite significant travel advantages for HOV lane users, the average travel speeds do not meet the minimum speed requirements for LOS C, and the Southeast Expressway facility in the p.m. peak period does not meet the 1-minute per mile savings required. MassHighway believes this latter measure is not a sign that the HOV lane is failing but rather that the general-purpose lanes are benefiting (i.e., able to maintain higher travel speeds) from the presence of the HOV lane. Rather than consider these facilities "failures," a closer look should be taken to ensure the regulation requirements are feasible for attainment.

The determination of air quality required more detailed data and analysis. For comparative purposes, "before" and "after" time periods were defined relative to the opening of the HOV lanes along the Southeast Expressway and the expansion (lengthening) of the HOV lanes along I-93 North. Additional investigations considered air quality effects of (1) changing the entry requirements from HOV-3+ to HOV-2+ along the Southeast Expressway and (2) restriping the southern terminus merge and extending the operating hours along I-93 North.

Emission factors were applied to respective average vehicle speeds per segment. In general, VOC and CO emissions decrease as speeds approach 55 mph and increase with higher

Table 14. Average Peak Period Performance Measures (Casey 2000).

	I-93 NORTH		SOUTHEAST EXPRESSWAY			
	Southbound a.m.		Northbound a.m.		Southbound p.m.	
HOV Lane Use (%)	33		21		17	
Travel Time Savings (min:sec/mile)	3:55		1:34		0:20	
Travel Speed (mph)	**HOV**	**GP**	**HOV**	**GP**	**HOV**	**GP**
	48	12	46	23	50	40
Travel Speed Difference (mph)	+36		+23		+10	

Table 15. Average Peak Period Air Quality Measures (Casey 2000).

CONDITIONS	EMMISSIONS			
	VOC (%)	NOx (%)	Summer CO (%)	Winter CO (%)
Southeast Expressway				
Before/After HOV Lane				
Constant Emissions Factors				
a.m. Peak	+8	-5	+6	+6
p.m. Peak	-1	+20	-1	-1
Alternative Emissions Factors				
a.m. Peak	-20	-16	-23	-12
p.m. Peak	-28	-3	-30	-20
3+ to 2+ Occupancy Change				
a.m. Peak	+9	+1	+12	+12
p.m. Peak	+2	-2	+4	+4
I-93 North				
Before/After Lengthening HOV Lane				
a.m. Peak	+8	+1	+7	+7
Restriping and Extending Hours				
a.m. Peak	+3	+3	+3	+3

speeds. NOx emissions decrease as speeds approach 20 mph and increase with higher speeds. The morning and afternoon emission results on the Southeast Expressway clearly reflect improved traffic operations in the afternoon, consistent with the performance report. The inverse relationship that NOx has to higher speeds, compared to other emittants, makes it unlikely that all three emittants will decrease. Of concern from an air quality standpoint is the increase in emissions in recent years and when the occupancy requirement was lowered to HOV-2+.

The difficult part of trying to quantify the HOV lanes' effect on air quality is that there are many factors beyond the control of any agency (i.e., natural growth in traffic, traffic on parallel, alternative routes) that may outweigh the HOV lane's benefit. In addition, the estimation of emissions is highly sensitive to the selection of the emissions factor, demonstrated when altering the emission factor and holding speed and volumes constant.

New York

The Long Island Expressway (LIE), I-495, extends from the Queens-Midtown Tunnel in New York City through the Borough of Queens into Nassau and Suffolk Counties, for a total length of 70 miles. Responding to a recommendation of the LIE/HOV Task Force, the New York State Department of Transportation (NYSDOT) implemented a comprehensive monitoring program to:

1. gather and evaluate data on HOV lane utilization, vehicle occupancy rates, travel speeds, compliance with HOV lane rules, etc.;
2. obtain feedback from HOV users and non-users; and
3. keep the public, media, elected officials, LIE/HOV Task Force, and other stakeholders informed about the HOV lanes (O'Connell et al. 2000).

Data to support these monitoring efforts are obtained in several ways: (1) HOV lane and general traffic volumes are collected automatically and continuously; (2) field observations are periodically undertaken to estimate vehicle occupancy rates, travel speeds, and HOV lane compliance rates; (3) surveys help understand user (and non-user) perceptions of the HOV lanes and obtain other important information about travel behavior patterns; and (4) focus groups have been conducted to gain public insights into HOV lanes and ridesharing.

Early in the planning phase for the LIE HOV lane system, a target threshold of 800 HOVs per hour was established as one measure of HOV lane effectiveness. Since implementation in 1994, the following trends in HOV lane usage, analyzed in terms of average annual weekday hourly traffic (AAWHT), are reported:

- During the first four years of HOV lane operation (when only a 12-mile HOV lane segment was in operation), AAWHT in the a.m. peak direction never reached the 800 HOVs per hour threshold; AAWHT in the p.m. peak direction reached this level of usage for only two of the five afternoon peak hours.
- During the fifth and sixth years of operation, AAWHT in the peak direction exceeded the 800 HOVs per hour threshold for seven of nine HOV reserved hours.
- During the sixth year of operation, AAWHT in the peak direction was approximately 1,000 or more HOVs per hour for five of nine HOV reserved hours.

- AAWHT increased 52 percent (from 660 to 1,000 HOVs) during the a.m. peak hour and 47 percent (from 870 to 1,275 HOVs) during the p.m. peak hour between the first year and sixth year of operation.

The average vehicle occupancy (AVO) has increased by 14.0 percent since the HOV lanes opened. During both the morning and the afternoon peak hours, the average speed in the general-purpose lanes parallel to the HOV lanes was determined to be approximately 40 mph, with speeds dipping to below 30 mph at a number of locations.

Comparison of HOV lane user surveys conducted in 1995, 1997, and 1999 revealed only slight differences in overall responses with one exception; reports of "new carpooling" have been steadily increasing. Notable findings from the 1999 survey include the following:

- 27 percent of users stated that they joined, formed, or increased the size of a carpool because of the HOV lanes. Factoring in their reported frequency of use of the HOV lanes and expanding survey population led to the estimate that the HOV lanes have directly contributed to more than 3,700 new regular carpoolers. In the 1995 survey, 6 percent of respondents said they joined or formed a carpool, while in the 1997 survey, 17 percent reported they did so.
- 74 percent of users stated that they used the HOV lanes to save time, 34 percent because they provided travel time reliability, and 21 percent cited cost savings as a reason for using the HOV lanes.
- Average reported travel-time savings was 15 minutes; 25 percent said the HOV lanes saved them more than 20 minutes in travel time.
- 56 percent of users agreed that the HOV lanes motivate people to carpool; 75 percent said the HOV lanes contribute to better traffic flow; 78 percent said they were safe to use; 79 percent felt they are less stressful to travel; and 81 percent said they should be extended in length.

At the same time the 1999 HOV lane user survey was conducted, license plates for a randomly selected sample of vehicles in the general-purpose lanes were recorded at the control site. Survey responses by general purpose travelers are provided for comparison:

- 28 percent agreed that the HOV lanes motivate people to carpool; 45 percent said the HOV lanes contribute to better traffic flow; 53 percent said they felt the HOV lanes were safe to use; 46 percent felt the HOV lanes are less stressful to travel; 51

percent felt the HOV lanes should be extended in length and 19 percent said the HOV lanes should not be extended.

- 13 percent stated the HOV lanes would not provide a time savings; 33 percent preferred to drive alone; and 35 percent said they could not find a carpool partner.

Texas

Following the national review of HOV lane performance conducted by Wellander and Leotta (2000), subsequent studies were conducted in Texas by Stockton et al. (2000) and Stockton and Daniels (2002). In *The ABCs of HOVs* (Stockton et al. 2000), the authors consider the effectiveness of various HOV lane facilities in Dallas and Houston in meeting the following prescribed objectives (see Table 16):

Increase Roadway Person-Movement

- person-movement characteristics of HOV lane and general-purpose lanes;
- percentage of persons moved versus the percentage of vehicles;
- percentage of persons moved versus the percentage of pavement used;
- increases in HOV lane use compared to overall increases in travel; and
- impact of HOV lanes on overall occupancy in the corridor.

Improve Bus Transit Operating Efficiency

- improvement in bus operating speeds that results from the free flow; and
- improvement in bus schedule reliability.

Improve Total Roadway Efficiency

- increase both the volume of people moved and the speed at which they move (i.e., person-movement × speed).

The authors cite secondary objectives (or "constraints") of HOV lane facilities as follows. HOV lanes should:

- have no impact on general-purpose lanes,
- be cost-effective,
- maintain public acceptance, and
- have a favorable or neutral impact on air quality and fuel consumption.

Table 16. Approximate Person-movement and Per Lane Efficiencies for Texas HOV Lanes (Stockton et al. 2000).

CITY	HOV FACILITY		PERSON MOVEMENT PER LANE		PERSON AND VEHICLE MOVEMENT PER LANE			PER LANE EFFICIENCIES	
			a.m. Peak		a.m. Peak				
			HOV	GP	HOV vehicle volumes/ vehicle volume (%)	HOV person movement/ person movement (%)	HOV lane use/total lane use (%)	Pre-HOV	Com-bined
Houston	Katy	reversible	3,500	1,750	25	40	15	37.5	90
	Gulf	reversible	3,000	1,500	20	32	15	65	87.5
	Southwest	reversible	4,000	1,750	17	31	15	62.5	100
	Northwest	reversible	3,500	2,000	25	37	18	62.5	102.5
	North	reversible	4,250	2,000	20	41	18	40	92.5
Dallas	E. R.L. Thornton	contraflow	4,000	2,000	20	35	16	40	90
	Stemmons	concurrent	2,250	2,000	25	27	15	55	65

In partial response to these secondary objectives, an evaluation study performed by Daniels and Stockton (2002) focused on the cost effectiveness of these same HOV lane facilities. In brief, the study considered aggregated construction costs, traffic data, geometric data, maintenance, operation, and enforcement costs, accident data, and HOV lane operational data (including type of HOV lane, vehicle classifications and occupancies, hours of operation, and percent of persons using the HOV lane) to develop benefit cost ratios for various facilities in Texas. Results from this study are summarized in Tables 17 and 18.

The results showed that the potential benefit of either alternative varies significantly by corridor. The role and effectiveness of the HOV lane varies significantly by type of lane (reversible, contraflow, or concurrent) and as total corridor traffic increases.

Table 17. B/C Ratios for Texas HOV Lanes (Stockton and Daniels 2002).

CITY	HOV FACILITY		BENEFIT TO COST RATIO
Houston	Katy	reversible	21
	Gulf	reversible	8
	Southwest	reversible	8
	Northwest	reversible	7
	North	reversible	6
Dallas	E. R.L. Thornton	contraflow	28
	Stemmons	concurrent	48

Table 18. B/C Ratios for Texas HOV Lanes versus a General Purpose Lane Alternative (Stockton and Daniels 2002).

CITY	HOV FACILITY		BENEFIT TO COST RATIO		ADDITIONAL BENEFIT PER DOLLAR SPENT (%)
			HOV Lane	Two GP Lanes	
Houston	Katy	reversible	15	9	67
	Gulf	reversible	9	4	125
	Southwest	reversible	8	5	60
	Northwest	reversible	7	6	17
	North	reversible	6	4	50
Dallas	E. R.L. Thornton	contraflow	28	10	180
	Stemmons	concurrent	48	43	12

Utah

In 2001, a 16-mile HOV lane facility opened on the reconstructed I-15. A single HOV lane operates in each direction separated from the four general-purpose freeway lanes by striping. The HOV lanes operate 24 hours and allow HOV-2+, motorcycles, and transit vehicles. HOV-only access is provided at 400 South, allowing HOVs direct access to the I-15 southbound on-ramp and I-15 northbound off-ramp.

A 2-year study evaluating the HOV lane performance was conducted by Martin et al. (2002), assessing the freeway operations before the HOV lanes opened with continued assessment throughout the first year of operation. Automatic data from traffic monitoring stations and manual data from roadside and travel time surveys provided information to evaluate HOV lane performance during the first year of operations. Key findings are summarized below.

- During the afternoon peak period, the HOV lane moves the same number of people as each GP lane with only 44 percent of the vehicles. The HOV lane moves fewer people than its GP lane counterparts throughout the rest of the day.
- Vehicle occupancy on the I-15 corridors with HOV lanes experienced a 17 percent increase, from 1.1 persons per vehicle to 1.3; average vehicle occupancy on I-215 and non-HOV portions of I-15 has remained the same.
- Relative to the adjacent GP lanes, the HOV lanes provide a 13 and 30 percent travel-time savings during the morning and afternoon and peak period, respectively.

- Violation rates range from 5 to 13 percent along the I-15 corridor. At the 400 South HOV on/off-ramp, violation rates increase to 20 percent. Violation rates initially reduced after the HOV lane opening and have since stabilized.

Washington

Most recent reported findings by Hallenbeck et al. (2004) from Seattle-area HOV facilities (between 2000 and 2002) reversed a decade-long trend in HOV use and performance. Instead of slowly growing, peak period HOV use remained steady or declined on many HOV corridors. Peak period HOV use was still heavy, despite the slight volume declines on several corridors. On many corridors, vehicle volumes on the HOV facilities approached or exceeded 1,500 vehicles per hour, and at several locations, HOV lane volumes still routinely exceeded GP lane volumes per lane. Most other HOV facilities carried approximately 1,000 vehicles during the peak hour. Regional system-wide averages are provided in Table 19.

The speed and reliability of travel in the HOV lanes generally improved between 2000 and 2002. By the end of 2002, 10 out of 14 HOV corridors performed above the speed and Washington State Department of Transportation (WSDOT)-prescribed reliability standard of 45 mph at least 90 percent of the time. The number of corridors where HOV lane travel times measured throughout the year fell below the adopted regional performance standard dropped from eight to five. These speed and reliability improvements were the result of several factors including the extension of the I-5 and I-405 HOV lanes that eliminated weaving movements at the previous HOV lane ending points, a slight reduction in peak period HOV volumes, and increased WSDOT emphasis on improving freeway operations through such programs as improved incident response.

Table 19. Average Person Throughput, Vehicle Volume, and Vehicle Occupancy for Seattle-area HOV Lanes (Hallenbeck et al. 2004).

TIME PERIOD		PERSON THROUGHPUT		VEHICLE VOLUMES		AVERAGE VEHICLE OCCUPANCY	
		HOV	GP	HOV	GP	HOV	GP
a.m. Peak	6:00–9:00 a.m.	7,070	5,497	2,395	4,703	3.35	1.17
p.m. Peak	3:00–7:00 p.m.	10,773	6,806	4,085	6,037	2.63	1.13
Off Peak	Per Hour			503	1,364		

Violation rates at most locations on most days were well below 5 percent. However, on specific days and/or at specific locations, violation rates may jump to more than 20 percent. Violations tended to increase just upstream of the locations where HOV lanes reverted to being GP lanes or led to exit ramps. The HERO program received 43,879 reports of violation in 2000, a 6 percent increase from 1999. Less than 6 percent of those reported were second-time offenders and less than 1 percent were three or more time offenders.

Georgia

HOV lanes were first implemented in metropolitan Atlanta in 1994, along an 18-mile section of I-20, east of I-75/85. An additional 60 lane miles opened on I-75/85 inside I-285 2 years later. Most recently in 2001, HOV lanes were extended approximately 11.8 miles on I-85, the first HOV lanes located outside of the I-285 perimeter. HOV lanes are viewed by the Georgia Department of Transportation (GDOT) as an integral part of the Georgia NAVI**GA**TOR intelligent transportation system (ITS), designed to help reduce air pollution, improve traffic congestion, and ensure a substantial time savings for commuters who rideshare. Eligibility is limited to vehicles carrying two or more occupants, certified alternative fuel vehicles, motorcycles, and emergency vehicles.

With more than a decade of HOV lane experience, GDOT is currently developing a comprehensive performance monitoring and evaluation plan specifically for the greater Atlanta HOV system with the goals of managing congestion; maximizing the use of carpools, vanpools, and transit; ensuring integration with transit; and attaining positive public perception.

In defining corresponding performance measures, GDOT recognized limitations related to data accuracy and frequency of collection, cost constraints, and a need to utilize existing infrastructure. Proposed performance measures and data collection methods are summarized in Table 20.

High-occupancy Vehicle Lane Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation, Table 21 summarizes relevant findings for HOV lane performance monitoring and evaluation based on a review of collective guidelines and site-specific evaluations.

Table 20. Proposed Performance Measures and Data Collection Methods in Georgia (GDOT, unpublished).

MEASURE		DATA COLLECTION METHODS
Key	Person Throughput	Average vehicle occupancy × number of vehicles, captured using automatic traffic recorders or other surveillance technologies by vehicle class.
Key	Vehicle Occupancy	Captured through manual sampling methods, with quarterly manual counts for the HOV lanes and annual manual counts for the general-purpose lanes on a site rotational basis.
Key	Travel Time Savings	General purpose - HOV travel times; captured using surveillance technologies, will undergo internal quality control reviews and will be supplemented with manual travel time runs.
Key	Travel Time Reliability	Expressed as the percent of time HOV lane speed drops below LOS or specified average speed; captured using surveillance technologies, will undergo internal quality control reviews and will be supplemented with manual travel time runs.
Key	Violations	Captured through enforcement records (i.e., citations, warnings) and reflected through average vehicle occupancy trends in the HOV lanes.
Complementary	Transit Utilization	Includes carpool, vanpool, and bus utilization of the HOV lane as well as bus ridership; captured using automatic traffic recorders or other surveillance technologies, bus ridership will be provided by transit agencies.
Complementary	Fuel Efficiency	General purpose - HOV fuel consumption, fuel consumption is estimated as a function of speed.
Complementary	Public Perception	Captured as part of a larger annual GDOT customer opinion survey.

Table 21. HOV Lane Performance Monitoring and Evaluation Summary.

GOALS/ OBJECTIVES		PERFORMANCE MEASURES		DATA COLLECTION																				EVALUATION/ MONITORING					
		MEASURES	OBSERVED PERFORMANCE/ TARGETS	Continuous Automated			Sampled, Manual			Customer Surveys				Agency Surveys															
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis			
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																												
	Increase throughput	• Daily, hourly volume on HOV facilities (vehicle, person) • Total, daily, and hourly facility volume (HOV, GP) • Total, daily, and hourly facility volume (vehicle, person)	[2] 1,100–5,250 pphpl, HOV, peak hour 190–1,713 vphpl, HOV, peak hour [5] 660–1,000 vphpl, a.m. peak 870–1,275 vphpl, p.m. peak [6] 2,250–4,250 pphpl, HOV, a.m. peak 1,500–2,000 pphpl, GP, a.m. peak	P				P	S												M Q A	M Q A	Q A	A	O	O			
		• Percent peak period volume (vehicle, person)	[6] 17%–25% HOV veh/total veh 27%–41% HOV per/total per	P				P	S												M Q A	M Q A	Q A	A	O	O			
		• Per-lane efficiency (speed × pphpl)	[1] 5%–20% increase, peak hour, facility [3] 11%–34% increase (range 72–98) [6] 18%–140% increase (range 65–102.5)	P	P		S	P	S												M Q A	M Q A	Q A	A	O	O			
		• Vehicle occupancy (per veh)	[1] >10% increase, peak hour, direction [3] 2%–11% increase (range 1.22–1.35) [5] 14% increase [8] range, 2.63–3.35 HOV, 1.13–1.17 GP [9] 17% increase (range 1.1–1.3)					P													M Q A	M Q A	Q A	A	O	O			
		• Transit ridership • Carpool use • Transit market share	[1] >20% increase in carpoolers 10%–20% increase on bus [2] 19%–32% increase in carpoolers 4%–6% increase on bus [3] 48%–53% HOV market share [4] 17%–33% HOV market share	P				P	S			P									M Q A	M Q A	Q A	A	O	O			
		• Mode shift	[2] 35%–66% of carpoolers drove alone 25%–46% of bus riders drove alone [5] 27% drove alone									P									M Q A	M Q A	Q A	A	O	O			

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually, O = one-time.

[1] Turnbull et al. (1991), [2] Wellander and Leotta (2000), [3] Bracewell et al. (1999), [4] Casey (2000), [5] O'Connell et al. (2000), [6] Stockton et al. (2000), [7] Daniels and Stockton (2002), [8] Hallenbeck et al. (2002), [9] Martin et al. (2002).

Table 21. HOV Lane Performance Monitoring and Evaluation Summary (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous, Automated			Sampled, Manual			Customer Surveys				Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION (Cont.)	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility (Cont.)																									
	Increase average travel speeds	• Average lane (HOV, GP) and facility speed	[3] +3.72–6.84 mph increase, GP [4] 12–40 mph, GP, 46–50 mph, HOV		P		S														M Q A	M Q A	Q A	A	O	O
	Decrease average travel times	• Travel time rate (min/mile)	[1] 1 min/HOV mile [2] 0.1–2.9 min/HOV mile [4] 0.33–3.55 min/HOV mile		P		S														M Q A	M Q A	Q A	A	O	O
		• Travel time savings (min) • Travel time savings ($/mile) • Annual travel-time savings ($)	[1] >5–7 min, peak hour [2] 3–41 min [3] 2.8–8.1 min [9] 13%–30% improvement		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on travel time	[5] 15 min avg. reported savings								P										A	A				
	Decrease violators	• Managed lane compliance	[3] 80%–85% compliance [8] 80%–95% compliance [9] 80%–95% compliance					S	P										S		M Q A	M Q A	Q A	A	O	O
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)	[3] SD 3.0–3.9, HOV SD 5.1–5.2, GP		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on reliability									P										A	A				
	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window	[1] >95% on-time		P		S								S						M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Turnbull et al. (1991), [2] Wellander and Leotta (2000), [3] Bracewell et al. (1999), [4] Casey (2000), [5] O'Connell et al. (2000), [6] Stockton et al. (2000), [7] Daniels and Stockton (2002), [8] Hallenbeck et al. (2002), [9] Martin et al. (2002).

Table 21. HOV Lane Performance Monitoring and Evaluation Summary (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	vehicle occupancy	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
SAFETY	**Increase overall safety levels**																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity																P	S		Q A	Q A		A	O	O
ENVIRONMENT	**Decrease overall impacts to the environment and resources**																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, PMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance	[4] +9% to -28% VOC +20% to -16% NOx +12% to -30% CO	P	P	S	S	S													Q A	Q A		A	O	O
ORGAN. EFFICIENCY	**Increase productivity without compromising public's expectations for efficient and effective travel**																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments	[2] 65%–94% rate HOVs "good"										P								A	A				
ORGAN. EFFICIENCY	Minimize costs	• Cost for construction (per lane-mile, VMT, PMT)		P				P	S								P				A O				O	O
ORGAN. EFFICIENCY	Minimize costs	• Vehicle operating costs (per lane-mile, VMT, PMT)	[1] 5%–20% improvement	P				P	S							P			S		Q A				O	O
ORGAN. EFFICIENCY	Minimize costs	• Cost-benefit measures	[7] 6–48 B/C	P	P		S									P	P	S	S		A				O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Turnbull et al. (1991), [2] Wellander and Leotta (2000), [3] Bracewell et al. (1999), [4] Casey (2000), [5] O'Connell et al. (2000), [6] Stockton et al. (2000), [7] Daniels and Stockton (2002), [8] Hallenbeck et al. (2002), [9] Martin et al. (2002).

VALUE-PRICED AND HIGH OCCUPANCY TOLL LANES

Collective Guidelines

Little documentation in the form of collective guidelines for monitoring and evaluation the performance of value-priced and high occupancy toll lanes was uncovered. In a single related document, DeCorla-Souza (2002) recommended a general analytical procedure for evaluating various value-priced and HOT lane scenarios. To demonstrate this procedure, the author considered (1) adding lanes (one in each direction) with no value pricing (i.e., base case), (2) charging peak-period tolls across an entire expanded facility (four lanes in each direction), (3) charging tolls on added lanes (one lane in each direction), leaving remaining lanes (three lanes in each direction) free of charge, and (4) providing two fast lanes and two regular lanes as part of a FAIR facility to a hypothetical 10-mile segment of congested roadway. The recommended procedure is provided below, followed by a summary of estimated results using the hypothetical 10-mile roadway segment [a more detailed analysis of FAIR lanes was also conducted by this same author (2001) and is described later in this report].

Evaluation Procedure

1. Estimate travel demand changes using a midpoint elasticity formulation (Pratt et al. 2000) with an assumed elasticity of -1 percent. This step requires estimation of a "price curve" (the relationship between variable travel costs faced by the user and traffic volume) where variable travel costs include the following:
   - Travel time costs estimated using a Bureau of Public Roads formulation with modified parameters calibrated for freeways (USDOT 1999). A value of time of $12 per vehicle hour (excluding commercial vehicles), updated to current dollars, is used to convert travel time to monetary cost (USDOT 1997).
   - Vehicle operating costs (excluding fuel costs and fuel taxes) are estimated at 7 cents per mile (USDOT 1992). Standard fuel costs are estimated at 3.3 cents per mile, inclusive of fuel taxes. Excess fuel consumption, as a result of congestion and calculated using FHWA's (2000) Highway Economic Requirements System (HERS) model, ranges from 0.037 gallons per minute of delay for a small car to 0.073 gallons per minute of delay for a sport utility vehicle, equating to 5 cents per minute of delay, inclusive of fuel taxes.

- For the toll scenarios, charges must be high enough in the priced lanes to ensure that total user travel costs for all lanes are in equilibrium; tolls are estimated as the difference between the lanes in remaining user costs.
- Other costs that are largely invariable, including auto insurance, agency costs, and parking, are excluded from this analysis.

2. Estimate economic benefit for each scenario using the micro economic social welfare analysis approach performed in HERS (FHWA 2000) where benefits include the following:
   - savings in variable costs for "old trips," calculated as the savings in travel time, vehicle operating costs, etc.;
   - losses incurred by disinduced trips (i.e., trips foregone due to higher travel costs); and
   - reductions in variable costs as a result of disinduced trips.

   Peak hour benefits are converted to average annual weekday benefits using a multiplier of 5.1 (assumes a peak hour volume equal to 9 percent of the daily traffic volume and a ratio of peak month average daily traffic volume to average annual daily traffic (ADT) of 1.1 to 1 [Transportation Research Board (TRB) 2001]. Annual benefits are estimated at 250 times average annual weekday benefits based on the number of working days in the year; weekend benefits are ignored to ensure conservative estimates.
3. Estimate economic costs using the following assumptions:
   - Capital costs for tolling an eight-lane facility are $1.5 million per mile; annual toll operation costs are $50,000 per mile. Capital costs for tolling a single lane are $0.75 million; annual toll operation costs are $25,000 per mile.
   - Construction costs for the added lanes are $10 million per lane-mile using the HERS model average costs for high-cost freeway widening (FHWA 2000).
   - Annual maintenance costs for existing and new lanes are $25,000 per lane-mile; $200,000 for an eight-lane facility.
   - The federally recommended discount rate of 7 percent is used to compute the present value of a 20-year stream of benefits and to annualize capital costs.

Hypothetic Results

DeCorla-Souza (2002) applied this procedure to each of the four scenarios described previously. The results of this analysis are provided in Tables 22 through 24.

Table 22. Peak-Hour Travel Demand and Variable User Costs (DeCorla-Souza 2002).

DESCRIPTION		DEMAND	USER TRAVEL COSTS	INDUCED TRAVEL	USER TRAVEL COST COMPONENTS					
					Time Cost	Vehicle Operating Cost	Fuel Cost	Fuel Tax	Tolls	Total User Charges
		veh/hr	¢/mi	veh/hr	¢/mi	¢/mi	¢/mi	¢/mi	¢/mi	¢/mi
Base	Added lanes, no value pricing	8,480	78	1,700	58.00	7.00	7.80	5.20	0.00	5.20
A	Peak period tolls on entire expanded facility (10¢/mi)	8,300	80	1,520	51.50	7.00	6.90	4.60	10.00	14.60
B	Existing “free” lanes (3)	6,420	82	-	61.25	7.00	8.25	5.50	0.00	5.50
	Added toll lane (1)	1,500	82	-	22.00	7.00	2.40	1.60	49.00	50.60
	All lanes combined (4)	7,920	82	1,140	-	-	-	-	-	-
C	Regular lanes (2)	4,380	82	-	69.25	7.00	9.45	6.30	-10.00	-3.70
	Fast lanes (2)	3,200	82	-	23.75	7.00	2.55	1.70	47.00	48.70
	All FAIR lanes combined (4)	7,580	82	800	-	-	-	-	-	-

Table 23. Peak Hour Benefits (DeCorla-Souza 2002).

DESCRIPTION		TOTAL VARIABLE COST	SAVINGS FOR “OLD” TRIPS	SAVINGS FOR DIS-INDUCED TRIPS	LOST BENEFITS	TOTAL BENEFITS
		¢/mi	$/dir/mi/hr	$/dir/mi/hr	$/dir/mi/hr	$/dir/mi/hr
Base	Added lanes, no value pricing	94.80	-	-	-	-
A	Peak period tolls on entire expanded facility (10¢/mi)	87.40	$614	$171	-$142	$643
B	Existing “free” lanes (3)	98.50	-$238	-	-	-
	Added toll lane (1)	53.40	$621	-	-	-
	All lanes combined (4)	-	$383	$531	-$448	$466
C	Regular lanes (2)	107.70	-$565	-	-	-
	Fast lanes (2)	55.30	$1,264	-	-	-
	All FAIR lanes combined (4)	-	$699	$853	-$720	$832

Table 24. Net Benefits of Alternatives Relative to Base Case (DeCorla-Souza 2002).

DESCRIPTION		COSTS million $/year	BENEFITS million $/year	NET BENEFITS million $/year
A	Peak period tolls on entire expanded facility (10¢/mi)	$2.00	$16.39	$14.39
B	Existing "free" lanes (3) and added toll lane (1)	$1.00	$11.89	$10.89
C	Regular lanes (2) and Fast lanes (2), FAIR lanes	$2.00	$21.22	$19.22

Site-specific Findings

A number of value-priced and HOT lane projects at various sites around the country were initiated through the Congestion Pricing Pilot Program [funded through the Intermodal Surface Transportation Efficiency Act (ISTEA)] and, more recently, the Value Pricing Pilot Program [VPPP, funded through the Transportation Efficiency Act for the 21st Century (TEA-21)]. Of most interest to this investigation are projects that are in the operational or demonstration phase, including sites in California, Texas, and Florida. Also included here, however, are the results of three feasibility studies that considered the potential impacts of value-priced and HOT lanes in California, Minnesota, and Georgia. Lastly, the results of two more focused studies that considered the impacts of FAIR lanes and the impacts of value pricing on commercial vehicles for a hypothetical site and various river crossings in New York/New Jersey, respectively, are included.

California

Value-priced and HOT lane projects in California include the following:

- State Route 91 in Orange County;
- I-15 in San Diego; and
- I-680 Sunol Grade in the San Francisco Bay Area.

State Route 91, Orange County. State Route 91 (SR-91), connecting employment centers in Los Angeles and Orange County with residential locations to the east, has the longest experience with variable pricing in the U.S. Open since December 1995, the privately built, operated, and maintained SR-91 Express Lanes (SR-91X), two in each direction, are 10 miles long and located in the median of the general-purpose lanes. Tolls currently range from $0.75 to $3.50 according to a fixed schedule that reflects time-of-day variations in congestion. Vehicles carrying three or more persons receive a 50 percent discount. Fares are automatically deducted from each customer's prepaid account using electronic transponders mounted on the car windshield. Over 100,000 motorists have SR-91X transponders (Berg 1999).

General performance results for this project are positive:

- patronage has steadily increased to the current level of 32,500 daily customers;
- users of the facility report time savings of up to 12 to13 minutes per trip;
- traffic on the adjacent mixed-use lanes is reported to be moving better than at any time since the early 1980s;
- the socioeconomic profile of transponder purchasers is similar to that of the average traveler in the corridor; and
- toll revenues are already exceeding the cost of operations and maintenance and are currently covering debt costs (Berg 1999).

In an extended monitoring and evaluation effort for this project, Sullivan (2000) more recently documented the wide range of impacts resulting from the introduction of value pricing along the SR-91 corridor. Key findings are provided in Table 25.

A related study conducted by Lam and Small (2001) considered specifically the value of time and reliability using observations from the SR-91 value-priced express lanes. Using simulation, the authors considered median travel times and reliability, defined as the difference between the 90th percentile and the median, for a free and variably tolled route. In addition, the authors combined route choice with other choices such as time of day of travel, car occupancy, and installation of an electronic transponder. The estimated value of time was estimated as $22.87 per hour. The value of reliability ranged from $15.12 per hour for men to $31.91 per hour for women. These values are 72 percent, 48 percent, and 101 percent, respectively, of the average wage rate in the sample.

Interstate-15, San Diego. Nearly 1 year after the opening of the SR-91 value-priced lanes in Orange County, an 8-mile reversible HOV facility in the median of San Diego's I-15 (Express Lanes) was opened to a limited number of paying SOVs who purchased monthly permits (ExpressPass). Prior to the initiation of this project, use of the HOV facility was restricted to carpools with two or more occupants, motorcycles, and emergency vehicles. The motivations for this project were to make better use of the HOV facility's available capacity and to raise revenues to support new transit service in the corridor (Berg 1999).

Table 25. SR-91X Performance Monitoring and Evaluation Results (Sullivan 2000).

GOAL AREA	RESULTS
Lane Utilization	• Peak (1998): 33,000 vehicles per day (vpd) (>14% of total SR 91 weekday ADT); current (2000): 24,000 vpd, impacted by opening of alternative toll route. • 7% of motorists use SR-91X in the midday off-peak; 35% of motorists use SR-91X in the p.m. peak. • Implied values of time for SR-91X users range from $6.00 to $14.40 per hour. • The proportion of motorists who use SR- 91X lanes at least some of the time increased from 28.2% in 1996 to 42.0% in 1999.
Travel Time and Delays	• After 6 months, p.m. peak delay fell from 30–45 min to 5–10 min per trip; delays increased gradually to the 30–40 min range, impacted by opening of alternative toll route; current p.m. peak delays are 30 min • Travelers typically overestimate their actual absolute time savings by 5-30 min
Mode shifts	• After 3 months, HOV-3+ jumped >40% in the p.m. peak period; before SR-91X opened, HOV-3+ vehicles averaged about 4% of the total SR-91 p.m. peak traffic. • SR-91X has not impacted public transportation patronage.
Public Opinion	• Approval of toll facilities remains high (50%–75%); approval of variable tolls decreased significantly from 55%–75% in 1996 to 30%–50% in 1999. • Approval for selling excess HOV lane capacity to SOV users is high (45%–75%), provided that the HOV lanes don't become congested.
Collision Experience	• SR-91X facility is operating at an acceptable level of safety; any observed increases in accident rates can be attributable to increased congestion levels.
Vehicle Emissions	• SR-91X vs. dual HOV lanes: assuming no change in VMT, the modeled emissions would be approximately the same. • SR-91X vs. general-purpose lanes: assuming a 7% increase in VMT, the modeled emissions would be approximately the same; for other assumptions on increased VMT (0%–10%), modeled emissions vary from -6% to + 3.7%. • SR-91X vs. no additional capacity: assuming an 8% increase in VMT, modeled emissions would be -18%.
Choice Modeling and Elasticity	• Price elasticity during the 6-hour period of heaviest use (morning westbound or afternoon eastbound) is consistently 0.7–0.8, a 10% across-the-board toll increase would result in about a 7%–8% decrease in toll facility use. Price elasticity during the 1-hour "peak of the peak" is 0.9–1.0. • When HOV-3+ users were charged a 50% toll, one-third of HOV-3+ traffic (about 2,000 vpd) moved from the SR-91X lanes to the free lanes. • Despite the 50% toll discount for HOV-3+ commuters, the difference in HOV-2 and HOV-3+ proportions is not statistically significant. • The percentage of SR-91X trips for the $40–$60K income category decreased from 40% in 1996 to 25% in 1999; middle income commuters may be more sensitive to toll increases.

Initially, permits were sold for $50 each to the first 500 subscribers. In February 1997, the number of subscribers increased to 700, and in March 1997, the monthly fee was raised to $70. The following month an additional 200 subscribers were added. Despite the fee increase from $50 to $70, 84 percent of the original customers opted to stay with the pilot program. Early travel-time savings were reported to be in the range of 10–20 minutes per trip (Berg 1999).

More than 2 years after its initial opening, the ExpressPass program was upgraded from its fixed monthly fee structure to a dynamic fee structure, varying charges by time of day and level of congestion. This dynamic pricing phase of the project was termed FasTrak. The highest tolls occur during peak hours of operation (5:30 a.m. to 9:30 p.m. and 2:30 p.m. to 7:30 p.m.), with tolls ranging from $0.50 to $4.00 under regular conditions. In rare instances, the San Diego Association of Governments (SANDAG) has the authority to allow tolls to increase to $8.00 per one-way trip. Charges can change every 6 minutes, jumping by $0.50 increments (Berg 1999).

To track the effects of this pricing structure evolution, a comprehensive monitoring and evaluation study was conducted by Supernak et al. (2003a) to investigate the use of value pricing as an instrument for better utilization of the HOT lanes along the I-15 corridor. Specifically, this study considered whether:

- LOS C was maintained on the I-15 Express Lanes;
- an improvement in the peak period I-15 Express Lanes utilization for either a.m. or p.m. peak periods resulted; and
- a shift from the middle of the peak toward the shoulders of the peak for either peak period resulted.

To investigate these objectives, the authors introduced the following measures:

- peak period utilization factor (PPUF) and
- peak period distribution factor (PPDF).

PPUF represents the reserve capacity in the express lanes and is defined as the ratio of total peak period volume (V) to the maximum peak period volume that maintains LOS C, which is defined as the product of the 15-minute threshold volume (TV_{15}) and the number of 15-minute segments (n_{15}) within a peak period (in percent):

$$PPUF = \frac{V}{TV_{15} x n_{15}}$$

An increase in PPUF would mean the reserve capacity available on the I-15 Express Lanes facility is diminishing, a desirable outcome.

PPDF reflects the actual distribution of volumes between the middle of the peak and the peak shoulders. PPDF is defined as the ratio of observed variance (S^2) of passage times to the variance assuming that traffic is uniformly distributed among the 15-minute segments within a peak period. In algebraic terms (in percent):

$$PPDF = \frac{12xS^2}{225x(n_{15}^2 - 1)}$$

An increase in PPDF would generally indicate flattening of the peak volumes and better utilization of the shoulders of the peak period, also a desirable outcome.

Supernak et al. (2003a) concluded that LOS C was maintained virtually at all times during study periods in 1997, 1998, and 1999. Instances where LOS C was exceeded accounted for approximately 1 percent of the time that the lanes were in operation. Findings related to changes in PPUF and PPDF are summarized in Table 26.

In a second study, Supernak et al. (2003b) investigated the impacts of value pricing on this corridor with respect to travel time and travel time reliability. Floating car travel time studies were performed during peak periods and over multiple years along a 5.9-mile segment of

Table 26. PPUF/PPDF Comparisons of I-15 Express Lane Volumes (Supernak et al. 2003a).

	SPRING				FALL			
	a.m. Peak		p.m. Peak		a.m. Peak		p.m. Peak	
	Percent Observed	Percent Change	Percent Observed	Percent Change	Percent Observed	Percent Change	Percent Observed	Percent Change
PPUF								
1996	N/A		N/A		41.5		47.7	
1997	45.1	N/A	51.3	N/A	45.4	9.4	55.9	17.
1998	46.9	3.9	58.0	13.2	53.3	17.2	57.3	2.5%
1999	53.0	13.1	60.6	4.4	58.2	9.4	65.7	14.6
1996-1999		N/A		N/A		40.3		37.7
PPDF								
1996	N/A		N/A		69.3		73.1	
1997	60.9	N/A	75.1	N/A	64.0	-7.6	75.9	3.8
1998	68.2	12.0	80.1	6.7	67.6	5.6	77.5	2.1
1999	69.4	1.8	80.	0.2	68.4	1.2	78.3	1.0
1996-1999		14.0		6.9		-1.3		7.1

I-15 to detect any temporal changes in performance. Similar data were collected along the I-8 "control" corridor to detect any confounding factors affecting performance. In general, the authors observed significant year-to-year changes in travel times along the I-15 mainlanes and the I-8 lanes. Variability on the I-15 Express Lanes was low; free-flow travel conditions were maintained at nearly all times. Results of the ramp delay study show that, in the worst-case scenario, I-15 Express Lane users can save up to 20 minutes per trip, avoiding approximately 4 and 16 minutes of delay on the I-15 mainlanes and on the ramp to the mainlanes, respectively.

Interstate-680 Sunol Grade, San Francisco Bay Area. Considering value pricing as an alternative to conventional HOV lane facilities, Kirshner (2001) used simulation to compare (1) separated and non-separated conventional HOV lanes with 2+ occupancy requirements, (2) a separated HOV lane that allows access by SOVs for a fee, and (3) a separated HOV lane with 3+ occupancy requirements that allows access by SOV and HOV-2 for a fee.

The Sunol Grade segment of I-680 in the San Francisco Bay Area provides a major gateway between suburban housing and Silicon Valley employment centers. The currently planned capacity expansion would add a single additional lane to the southbound side of Sunol Grade, which handles the heavier morning peak commute. The original proposal would operate this lane as an HOV lane open to vehicles with 2+ occupants. The high proportion of vehicles with two or more people already traveling in the corridor may immediately fill the HOV lane. The alternative of restricting the lane to 3+ vehicles may result in a perceived underutilization of the lane. Hence, value pricing was considered as a compromise between the two conventional HOV alternatives. Results from the simulation are summarized in Tables 27 and 28.

Table 27. Comparison of Conventional and Value-priced Alternatives (Kirshner 2001).

	HOV-2+	HOV-2+, SEPARATED	HOV-2+, SEPARATED, SOV BUY-IN	EXPRESS LANE, HOV-3+ FREE, SEPARATED
FEATURES				
Unlimited, free access available to…	HOV-2+	HOV-2+	HOV-2+	HOV-3+
Limited access available to…	None	None	SOV	HOV-2, SOV
Barriers	None	Yes	Yes	Yes
Serves evening commute	No	Yes	Yes	Yes
New lane throughput capability (vphpl)	1,700	2,100	2,100	2,100
RESULTS (25% increase in travel demand, person-hours delay during morning peak period)				
General purpose lanes	2,874	2,180	1,503	1,453
New lane	1,305	749	519	0
Total	4,180	2,929	2,021	1,453

Table 28. Calculation of Delay for 3+ HOV/Value-priced Alternative (Kirshner 2001).

TIME	ARRIVAL RATE		THROUGHPUT CAPACITY		VEHICLES IN QUEUE		THROUGHPUT		DELAY		PERSON-HOURS OF DELAY		TIME ADVANTAGE	FRACTION PERSONS HOV-2	FRACTION PERSONS HOV-3+
	veh/hr		veh/hr		veh		veh/hr		hr:min		per-hr		hr:min		
	GP	VP	GP	VP	GP	VP	GP	VP	GP	VP	GP	VP	VP	VP	VP
5:00			6,300	2,100	0	0			0:00	0:00					
5:30	5,852	2,100	6,300	2,100	0	0	5,852	2,100	0:00	0:00	0	0	0:00	0.238	0.127
6:00	6,044	2,100	6,300	2,100	0	0	6,044	2,100	0:00	0:00	0	0	0:00	0.238	0.127
6:30	7,248	2,100	4,200	2,100	1,524	0	4,200	2,100	0:12	0:00	256	0	0:12	0.220	0.194
7:00	3,991	2,100	4,577	2,100	1,231	0	4,577	2,100	0:18	0:00	687	0	0:18	0.209	0.234
7:30	3,250	2,100	6,300	2,100	0	0	5,712	2,100	0:00	0:00	510	0	0:00	0.238	0.127
8:00	2,045	2,100	6,300	2,100	0	0	2,045	2,100	0:00	0:00	0	0	0:00	0.238	0.127
8:30	2,046	2,100	6,300	2,100	0	0	2,046	2,100	0:00	0:00	0	0	0:00	0.238	0.127
9:00	2,057	2,100	6,300	2,100	0	0	2,057	2,100	0:00	0:00	0	0	0:00	0.238	0.127
9:30	2,340	2,100	6,300	2,100	0	0	2,340	2,100	0:00	0:00	0	0	0:00	0.238	0.127
10:00	2,443	2,100	6,300	2,100	0	0	2,443	2,100	0:00	0:00	0	0	0:00	0.238	0.127

Texas

Interstate-10 (Katy Freeway), Houston. Following the completion of a multi-year feasibility study conducted under the sponsorship of the Congestion Pricing Pilot Program, the QuickRide project was launched on an existing HOV lane of the Katy Freeway (I-10). This project allowed a limited number of HOV-2 carpools to purchase entry into a reversible HOV lane normally restricted to vehicles with 3+ occupants during the peak-travel periods. During this time period, participating HOV-2 vehicles paid a $2.00 per trip fee while HOV-3+ vehicles continue to travel free. Single-occupant vehicles were not allowed to use the HOV lane (Berg 1999).

Prior to initiation of the QuickRide project, the three main freeway lanes carried approximately 5,200 vehicles or about 6,000 persons per hour travel (2,000 persons per hour per lane). Speeds on the mainlanes averaged about 24.9 mph in both the morning and evening peak periods. About 600 vehicles or 4,000 persons per hour traveled on the single HOV lane at speeds of 53 to 56 mph in the morning and 59 to 62 mph in the evening peak (Berg 1999).

To preserve the higher levels of service experienced in the HOV lanes, the number of HOV-2 vehicles scheduled to participate in QuickRide was initially limited to 300. Following an initial evaluation of peak-period traffic conditions under the QuickRide demonstration, up to 300 additional HOV-2 vehicles were allowed to participate (Berg 1999).

With overall objectives to (1) increase overall person throughput in the Katy Freeway corridor during peak periods; (2) increase travel speeds on mixed-flow lanes during peak periods, assuming a number of vehicles currently using the general-purpose lanes will divert to the HOV lane; and (3) effectively manage demand without adverse operating impacts on both the HOV lane and GP lanes; the QuickRide has been periodically evaluated and monitored since its inception. An early study of the QuickRide program (Shin and Hickman 1999) indicated that the first two objectives were generally not met during the first 6 months of demonstration due to a much lower than anticipated demand for HOV lane access. Similar conditions were also observed during the second half of the demonstration in fall 1998. The most recent investigation (Hickman et al. 2000) considered possible travel behavior characteristics to explain this phenomenon.

Automatic vehicle identification (AVI) estimated travel times for the corridor. A mail-back traveler survey captured additional travel information both before and after QuickRide implementation to determine mode and time shifts and demographic characteristics correlating with participants' frequency of use. Findings from this investigation are summarized in Table 29.

Florida

Cape Coral and Midpoint Memorial Bridge, Lee County. In the same year that Texas introduced the QuickRide program along I-10 in Houston, variable pricing was initiated to improve efficiency and travel times on two bridges in Lee County, Florida, with the goals of shifting traffic out of the peak travel period, reducing congestion and emissions, and postponing the need for future capacity expansion. Total "before" volumes on the bridges on an average weekday varies between 60,000 and 65,000 vehicles.

Table 29. I-10 Performance Monitoring and Evaluation Results (Hickman et al. 2000).

GOAL AREA	RESULTS
Lane Utilization	• a.m. peak: 50–90 vehicles per day • p.m. peak: 40–50 vehicles per day • Average number of uses per week is approximately 0.89; 70% of participants use it less than once per week
Travel Time and Delays	• a.m. peak: HOV travel speeds ranged from 40 to 63 mph, GP travel speeds ranged from 12 to 45 mph • p.m. peak: HOV travel speeds ranged from 54 to 75 mph, GP travel speeds ranged from 15 to 34 mph • No substantive evidence exists that links this speed differential to the existence of the QuickRide program separate from the HOV lane • Average travel-time savings were 19.3 and 21.4 minutes in the a.m. and p.m., respectively; travel-time savings ranged from 5 to 51 and 9 to 39 minutes in the a.m. and p.m., respectively • Value of travel time equates to $6.00 per hour ($2.00 per tip/20 min time savings)
Temporal Shifts	• One-third of QuickRide trips involve a change in time of travel from the shoulders into the peak period • 10% (a.m.) and 3.6% (p.m.) of QuickRide trips are HOV-2 shifting from the shoulders into the peak hour
Mode Shifts	• 51% (a.m.) and 58% (p.m.) are from SOVs moving into the HOV lane • 23% (a.m.) and 29% (p.m.) of QuickRide trips are HOV-2 moving from the main freeway lanes to the HOV lane • Bus ridership, in favor of lower occupancy modes, decreased by 11% (a.m.) and 5% (p.m.)

The Lee County program provided bridge patrons with a 50 percent discount during selected off-peak hours or peak shoulders as incentive to change trip-making times from peak to off-peak hours; the full toll rate is $1 for each way bridge crossing. Eligibility for the discounted toll rate was limited to patrons utilizing electronic responders and driving two-axle vehicles.

Considering only the first 5 months of operation, Swenson et al. (1999) reported observed performance of value pricing on the bridge facilities. Overall, the data indicated bridge travelers were responding to variable pricing as predicted, shifting their travel times from peak periods to discount periods (see Table 30).

Table 30. Cape Coral and Midpoint Memorial Bridge Change in Average Daily Traffic (Swenson et al. 1999).

TIME		CAPE CORAL BRIDGE	MIDPOINT MEMORIAL BRIDGE
Morning Peak	7:00 a.m. - 9:00 a.m.	-70	-101
Morning Discount	6:30 a.m. - 7:00 a.m. 9:00 a.m. - 11:00 a.m.	+94	+89
Afternoon Peak	4:00 p.m. - 6:30 p.m.	-20	-67
Afternoon Discount	2:00 p.m. - 4:00 p.m. 6:30 p.m. - 7:00 p.m.	+50	+70

Investigators took a closer look at the change in average daily bridge traffic by segregating those eligible and not eligible for the variable pricing discounts. On the Midpoint Memorial Bridge, only one half-hour period (9:30 a.m. to 10:00 a.m.) showed a significant change (at the 95 percent confidence interval) in traffic volumes. On the Cape Coral Bridge, nine half-hour periods showed significant changes. These changes appear to follow typical seasonal fluctuations in Lee County caused by tourists in the spring and are all less than 5 percent.

Considering the eligible patron data, (approximately 23 percent of bridge traffic) most half-hour time periods during discount hours experienced a significant increase in traffic while traffic decreased significantly during peak periods. These changes to traffic patterns clearly show that variable pricing is meeting its goal and drivers are altering their travel behavior due to variable pricing.

In a follow-up study conducted by Burris and Swenson (2001), similar findings were observed. Most half-hour time periods during discount hours experienced a significant increase in eligible user traffic, while eligible user traffic decreased significantly in the peak period. No accompanying changes in vehicle speeds or average vehicle occupancies have been observed. Results from a companion survey of patrons indicate that more than 71 percent changed the time of day that they travel at least once per week to take advantage of the variable pricing discount.

Minnesota

I-394, Minneapolis. Without actual implementation, He et al. (2001) considered conversion of existing HOV lanes along I-394 in Minneapolis to barrier-separated HOT lanes, used by HOVs at no charge and by SOVs for a fixed toll. The HOV facilities under study are located along a 10-mile stretch of I-394, connecting the western suburbs with downtown Minneapolis and comprising a barrier-separated two-lane HOV section with exclusive ramps and a non-separated one-lane HOV section. Both HOV sections are operating only during the morning and afternoon peak periods.

Using traffic simulation, the impacts of the proposed HOV to HOT conversion along the I-394 corridor related to average travel speeds and total travel times were estimated. He et al. (2001) developed separate estimates based on the:

- time of day (a.m. or p.m. peak),
- SOV toll rate ($0.0, $0.25, $0.50, $0.75, $1.00, $1.25, and $1.50),

- percentage of SOVs that switch to HOV (0, 15, and 30 percent),
- percentage of current origin-destination (O-D) demands (100, 94, 88, and 110 percent), and
- perception error percentage (i.e., perceived versus actual travel time, 0 and 15 percent).

Investigators assumed a constant value of time of $6 per hour. An abbreviated summary of key findings is provided in Table 31.

As part of this investigation, a driver perception survey was conducted to gage public acceptance of the HOV to HOT conversion. As reported here, 53 percent of the respondents would be willing to use the toll lane with a one-way toll ranging from $0.10 to $2.00 and a mean toll rate of $0.71.

Table 31. Simulated I-394 Performance Results (He et al. 2001).

AVERAGE SPEED (mph)		SOV TOLL RATE ($)	CURRENT O-D (%)	MODE SPLIT (SOV:HOV)	PERCEPTION ERROR (%)
a.m. Peak					
Maximum	30.3	0.25–1.25	88	66:34	0–15
Minimum	26.6	1.50	110	82:18	0–15
p.m. Peak					
Maximum	29.2	0.25	88	64:36	0–15
Minimum	23.5	1.00–1.50	110	80:20	0–15
TOTAL TRAVEL TIME (veh-hrs)		**SOV TOLL RATE ($)**	**CURRENT O-D (%)**	**MODE SPLIT (SOV:HOV)**	**PERCEPTION ERROR (%)**
a.m. Peak					
Minimum	26,485	0.25	88	66:34	0–15
Maximum	66,029	0.50	110	82:18	0–15
p.m. Peak					
Minimum	80.881	0.25	94	72:28	0–15
Maximum	130,712	1.50	110	80:20	0–15

Georgia

Metropolitan Atlanta Area. A similar feasibility study was recently conducted by Parsons, Brinkerhoff, Quade, and Douglas (PBQD 2005) to investigate the potential for implementing HOT lanes along various highways of metropolitan Atlanta and the Georgia 400 Corridor by the year 2030. Three major pricing strategies were assessed: (1) charging SOVs a fee to use a managed lane (assuming that uncongested level of service can be maintained); (2) charging all vehicles with less than three occupants a fee to use the lanes; and (3) charging all vehicles with less than four occupants a fee to use the managed lanes. All transit vehicles and carpools of more than four people would ride for free. In addition to these pricing strategies, a scenario was tested for comparison purposes that limited managed lane use only to those vehicles with three or more people; no other vehicles were allowed in the lane.

The demand for HOT managed lane use varied from one road corridor to another, depending on which pricing strategy was assumed. For example, requiring all vehicles with three or fewer occupants to pay a fee provides the greatest vehicle-carrying demand for HOT managed lanes on I-285N of all the scenarios tested. However, for I-75S and I-85S, the pricing strategy that produced the largest number of vehicle trips in the managed lanes was to charge a fee only to single occupant vehicles. Additional results are summarized in Tables 32 and 33.

Table 32. Simulated Metropolitan Atlanta Area HOT Lane Utilization (PBQD 2005).

EVALUATION SCENARIOS	CORRIDORS ON I-285			CORRIDORS INSIDE I-285			CORRIDORS OUTSIDE I-285		
	Vehicle Trips	Person Trips	VMT	Vehicle Trips	Person Trips	VMT	Vehicle Trips	Person Trips	VMT
Current HOV policy	333	922	2,089	456	1,274	1,585	546	1,511	3,601
HOV-3+ can use	234	820	1,528	347	1,223	1,266	370	1,303	2,508
SOVs pay fee to use	413	1,023	2,512	489	1,175	1,503	885	1,849	5,431
<3+ vehicles pay fee to use	360	994	1,960	410	1,147	1,176	715	1,684	4,176
Vehicles with <4 pay fee to use	347	774	1,245	452	1,149	938	690	1,418	3,340

Table 33. Simulated Metropolitan Atlanta Area HOT Lane Trip Time Savings (PBQD 2005).

VEHICLE ELIGIBILITY STRATEGY	P.M. PEAK PERIOD TIME SAVED IN HOT MANAGED LANE (minutes)			
	Single occupant vehicles pay fee to use managed lanes		Vehicles with less than three occupants pay fee to use managed lane	Vehicles with less than four occupants pay fee to use managed lane
	2015	2030	2030	2030
Midtown Atlanta to South Lake Mall		18	19	18
Airport to Midtown Atlanta		14	8	12
I-75 at I-285 to Town Center Mall		25	25	29
Alpharetta to Airport		12	13	13
Perimeter Center to Town Center Mall		17	25	27
Midtown Atlanta to Douglasville		16	16	20
Stonecrest Mall to Airport		9	9	9
Mall of Georgia to Airport		13	23	22
GA 400: Northbound from I-285 to Alpharetta (SR 120)	10	N/A	15	18
GA 400: Southbound from McFarland Road to I-285	4	N/A	7	9

To assess the cost effectiveness of HOT operations, potential revenues were calculated based on miles traveled in a HOT corridor and the fee rate for that corridor. Requiring vehicles with less than four occupants to pay a fee to use the managed lane generates the most revenue (because it charges the most users in each HOT corridor). This is the only pricing strategy that resulted in potential revenues higher than estimated costs to implement the HOT concept at the system level. Certain corridors under each scenario, however, do generate potential revenue that covers operations and maintenance costs of the HOT managed lane(s) in that corridor. For example, the strategy of having SOVs pay fees to use the managed lanes for I-75N and I-75S (both outside I-285) covers the incremental capital and operation and maintenance costs associated with the managed lanes in each corridor.

FAIR Lanes, Hypothetical Scenario

With a more narrowed focus, DeCorla-Souza (2001) estimated the potential impacts of FAIR lanes for a hypothetical scenario. Recall that the concept of FAIR lanes involves separating congested freeway lanes into fast lanes and regular lanes. The fast lanes are electronically tolled express lanes with tolls set in real time to limit the traffic and prevent congestion. In the regular lanes, constricted traffic continues but drivers are rewarded with credits that may be used as toll payments on days when they choose to use the fast lanes.

Tables 34 through 36 summarize the estimated FAIR lane performance and financial and economic efficiency impacts for a prototypical eight-lane freeway with four lanes in each direction. The prototype freeway has a 10-mile severely congested segment with constricted flow complicated by interchanges at approximately 1-mile intervals. The segment has an average daily traffic volume of 208,000. Under the FAIR lanes scenario, the existing four lanes in each direction will be divided into two sections: two fast lanes and two regular lanes. Exits would be by way of direct connector ramps.

Commercial Vehicle Impacts, Port Authority of New York and New Jersey

Again with a more narrowed focus – on a sector of the motoring public rather than a particular value pricing strategy – Vilain and Wolfrom (2000) considered the effects of value pricing on freight traffic. The investigators considered six interstate crossings between New Jersey and New York City including the George Washington Bridge, Lincoln Tunnel, Holland Tunnel, Goethals Bridge, Outerbridge Crossing, and Bayonne Bridge.

Table 34. Performance Impacts of FAIR Lanes (DeCorla-Souza 2001).

	BASE CASE	FAIR LANES		
	All Lanes	**Fast Lanes**	**Regular Lanes**	**Total**
Traffic Volumes (vph)				
3:30–4:30 p.m.	5,800	4,000	2,900	6,900
4:30–5:30 p.m.	5,800	4,000	2,900	6,900
5:30–6:30 p.m.	5,800	4,000	2,900	6,900
6:30–7:30 p.m.	5,800	4,000	2,900	6,900
Total	23,200	16,000	11,600	27,600
Average Speeds (mph)				
3:30–4:30 p.m.	28.87	60.00	28.87	41.29
4:30–5:30 p.m.	24.31	60.00	24.31	37.10
5:30–6:30 p.m.	23.30	60.00	23.30	36.10
6:30–7:30 p.m.	26.26	60.00	26.26	38.96
Average	25.51	60.00	25.51	38.26
Delay (min/mi)				
3:30–4:30 p.m.	1.08	0.00	1.08	
4:30–5:30 p.m.	1.47	0.00	1.47	
5:30–6:30 p.m.	1.58	0.00	1.58	
6:30–7:30 p.m.	1.28	0.00	1.28	
Average	1.35	0.00	1.35	
Total Delay for 10-mile segment, both directions (hours)				
3:30–4:30 p.m.	2,085	0	1,042	1,042
4:30–5:30 p.m.	2,838	0	1,419	1,419
5:30–6:30 p.m.	3,045	0	1,523	1,523
6:30–7:30 p.m.	2,484	0	1,242	1,242
Total	10,452	0	5,226	5,226

Table 35. Financial Impacts of FAIR Lanes (DeCorla-Souza 2001).

	FAIR LANES		
	Fast Lanes	**Regular Lanes**	**Total**
Toll Rate (cents/mile)			
3:30–4:30 p.m.	14.4	-7.2	
4:30–5:30 p.m.	19.6	-9.8	
5:30–6:30 p.m.	21.0	-10.5	
6:30–7:30 p.m.	17.1	-8.6	
Average	18.0	-9.0	
Annual Revenues for 10-mile Segment, Both Directions (million $)			
p.m. Peak Period	14.42	-5.23	9.19
a.m. Peak Period	7.21	-2.61	4.60
Total	21.63	-7.84	13.79
Annualized Capital and Operation and Maintenance Costs (million $)			
Toll/credit Transaction Costs	2.00	2.00	4.00
Direct Connector Ramp Costs	2.00	0	2.00
Total	4.00	2.00	6.00
Surplus of Revenues over Costs (million $)			7.79
Annual Fuel Consumption (million gallons)	4.80	4.30	9.10
Annual Gas Tax Receipts (million $)	1.92	1.72	3.64

Table 36. Economic Efficiency of FAIR Lanes (DeCorla-Souza 2001).

USER BENEFITS	
Mobility Benefits	
Total Time Saved by p.m. Peak Travelers (hours/day)	360.42
Total Annual Mobility Benefits (million $)	32.44
Out-of-Pocket and Fuel Cost Changes	
Net Annual Tolls (i.e., tolls less credits, million $)	13.79
Annual Fuel Cost Changes (million $)	-1.59
Net Annual User Benefits	20.24
ANNUAL EMISSION COST CHANGES	
Hydrocarbon (HC) Emissions Change (tons/year)	-71.43
CO Emissions Change (tons/yr)	-273.82
NOx Emissions Change (tons/yr)	133.60
Total Emissions Cost Change (million $)	-0.33
SUMMARY OF BENEFITS AND COSTS (MILLION $ ANNUALLY)	
User Benefits	20.24
Emissions Benefits	0.00
Net Revenues to Toll Agency	13.79
Loss of Fuel Tax Receipts to Government	-0.45
Total Annual Benefits	33.57
Annualized Costs (million $)	6.00
Benefit/Cost Ratio	5.60

These crossings are crucial to the flow of commercial traffic within the region, providing the primary road link between New York City and Long Island and New Jersey and other points to the west. Further, a significant volume of traffic bound for New England also uses various interstate crossings, particularly the George Washington Bridge. Trucks are currently charged a toll in the eastbound direction of $4 per axle, which equals $16 for the typical large truck.

The task of this investigation was to determine the importance of this toll as a percentage of the generalized cost of travel (GCT) facing trucks making a peak-period interstate crossing. A congestion surcharge that only marginally affects the GCT may not significantly change the behavior of these trucks and, hence, may lessen the desired effects of value-pricing strategies.

The analysis relied upon the Port Authority's Interstate Network Analysis (INA) regional traffic assignment model to estimate the total peak-period travel time for trucks making trips between each origin-destination pair contained in the model. This estimate was also combined with an estimate of the total distance traveled on each origin-destination pair. After reasonable estimates were assigned for the value of time of trucks and vehicle operating cost per mile, estimates of the peak-period GCT for all origin-destination pairs were derived. Since the INA model also accounts for tolls, the estimates included tolls charged at the interstate crossings.

The analysis revealed that commercial traffic using the New York/New Jersey interstate crossings does try to spread its peak period to a degree. However, even despite these efforts, the hours of heaviest use of the crossings are similar to those of other vehicle types, meaning that commercial traffic is a major contributor to peak-period congestion. Limited delivery windows, operating hours of piers, curfews, union regulations, regional geography (i.e., a trucking firm making an eastbound crossing will do so early enough to be able to schedule a profitable number of pickups and deliveries in New York City and Long Island; likewise, crossings made before 5 a.m. translate into drivers being idle, even if deliveries begin in Manhattan as early as 7 a.m.) are just a few of the constraints facing commercial vehicles cited by the investigators.

To determine whether commercial vehicles would respond to value pricing, an analysis of the generalized cost of travel facing trucks using the crossings was performed. Current tolls account for between 10 and 29 percent of the GCT, depending on origins and destinations. Assuming that doubling of the tolls was politically feasible, this would increase the total GCT by 10 to 29 percent. Given the highly competitive nature of the trucking industry, it is assumed that these costs would be mostly passed on to producing firms. However, the factor costs that make up the GCT are only one aspect of the logistics costs facing producing firms, for which the costs of switching to off-peak deliveries may far outweigh the higher peak-period tolls.

A tentative conclusion of the analysis is that "realistic" value pricing scenarios may result in only modest changes in behavior by commercial traffic. The costs of shifting to off peak are apparently too high in most cases. Further, it is not clear that a congestion surcharge would not simply be passed on to customers as a uniform rate increase, regardless of the delivery time. In this case, one of the implicit objectives of a congestion surcharge, making the customer assume the marginal social cost of the peak-period delivery, would not be achieved.

Value-priced and HOT Lane Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation, Table 37 summarizes relevant findings for value-priced and HOT lane performance monitoring and evaluation based on a review of collective guidelines and site-specific evaluations.

Table 37. Value-priced and High Occupancy Toll Lane Performance Monitoring and Evaluation Summary.

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	Continuous Automated: speeds/travel times	Continuous Automated: density/lane occupancy	Sampled, Manual: travel times	Sampled, Manual: vehicle occupancy	Sampled, Manual: violation rates	Customer Surveys: origin-destination	Customer Surveys: perceived time savings	Customer Surveys: ridership/mode use	Customer Surveys: satisfaction	Agency Surveys: vehicle productivity	Agency Surveys: on-time performance	Agency Surveys: operating costs	Agency Surveys: capital costs	Agency Surveys: accidents	Agency Surveys: enforcement levels	Agency Surveys: toll revenue	EVALUATION/ MONITORING: descriptive statistics	EVALUATION/ MONITORING: inferential statistics	EVALUATION/ MONITORING: capacity analysis	EVALUATION/ MONITORING: simulation	EVALUATION/ MONITORING: before and after analysis	EVALUATION/ MONITORING: alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
MOBILITY/CONGESTION	Increase throughput	• Daily, hourly volume on HOV facilities (vehicle, person) • Total, daily, and hourly facility volume (HOV, GP) • Total, daily, and hourly facility volume (vehicle, person)	[3] 7% (off peak) to 35% (p.m. peak) use lane (range 24,000–33,000 vpd) [6] 50–90 vpd, a.m. peak 40–50 vpd, p.m. peak 0.89 avg. uses per week [4] 2.5%–17.2% increase in PPUF (range 45.1%–65.7%)	P				P	S												M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase throughput	• Vehicle occupancy (per/veh)						P													M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase throughput	• Temporal shift	[4] -7.6%–12.0% increase in PPDF (range 60.9%–80.3%) [6] 10% (a.m.) and 3.6% (p.m.) are HOV-2 paying toll to move to peak out of shoulders [7] 70%–101% (a.m.) and 20%–67% (p.m.) decrease in ADT 89%–94% (a.m.) and 50%–70% (p.m.) increase in ADT during discounted periods [8] 71% changed time of travel 1+ times/week	P				P	S												M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase throughput	• Mode shift	[3] HOV-3+ increased 4%–40% [6] 51% (a.m.) and 58% (p.m.) drove alone 11% (a.m.) and 5% (p.m.) changed from bus to carpool									P									M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] DeCorla-Souza (2002), [2] Berg (1999), [3] Sullivan (2000), [4] Supernak et al. (2003a), [5] Supernak et al. (2003b), [6] Hickman et al. (2000), [7] Swenson et al. (1999), [8] Burris and Swenson (2001), [9] He et al. (2001), [10] PBQD (2005), [11] DeCorla-Souza (2002).

Table 37. Value-priced and High Occupancy Toll Lane Performance Monitoring and Evaluation Summary (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	vehicle occupancy	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION (Cont.)	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility (Cont.)																									
	Increase average travel speeds	• Average lane (HOV, GP) and facility speed	[6] 40–63 mph HOV, 12–45 mph GP, a.m. peak (not exclusive of HOV lane effects) 54–75 mph HOV, 15–34 mph GP, a.m. peak (not exclusive of HOV lane effects)		P		S														M Q A	M Q A	Q A	A	O	O
	Decrease average travel times	• Travel time savings (min) • Travel time savings ($/mile) • Annual travel-time savings ($)	[2] 12–13 min/trip [5] 20 min/trip [6] 19.3 min/trip, a.m. peak (range 5–51 min) 21.4 min/trip, p.m. peak (range 9–39 min) [10] 7–29 min/trip, p.m. peak, simulated 2030		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on travel time									P										A	A				
	Decrease delay	• Average delay (per day, annually) • Average delay (vehicle, person)	[11] 360.42 hours/day, p.m. peak	P	P		S	S	S												M Q A	M Q A	Q A	A	O	O
	Decrease violators	• Managed lane compliance						S	P										S		M Q A	M Q A	Q A	A	O	O
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on reliability									P										A	A				
	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S								S						M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] DeCorla-Souza (2002), [2] Berg (1999), [3] Sullivan (2000), [4] Supernak et al. (2003a), [5] Supernak et al. (2003b), [6] Hickman et al. (2000), [7] Swenson et al. (1999), [8] Burris and Swenson (2001), [9] He et al. (2001), [10] PBQD (2005), [11] DeCorla-Souza (2002).

Table 37. Value-priced and High Occupancy Toll Lane Performance Monitoring and Evaluation Summary (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous, Automated: volumes/classifications	Continuous, Automated: speeds/travel times	Continuous, Automated: density/lane occupancy	Sampled, Manual: travel times	Sampled, Manual: vehicle occupancy	Sampled, Manual: violation rates	Customer Surveys: origin-destination	Customer Surveys: perceived time savings	Customer Surveys: ridership/mode use	Customer Surveys: satisfaction	Agency Surveys: vehicle productivity	Agency Surveys: on-time performance	Agency Surveys: operating costs	Agency Surveys: capital costs	Agency Surveys: accidents	Agency Surveys: enforcement levels	Agency Surveys: toll revenue	EVALUATION/ MONITORING: descriptive statistics	EVALUATION/ MONITORING: inferential statistics	EVALUATION/ MONITORING: capacity analysis	EVALUATION/ MONITORING: simulation	EVALUATION/ MONITORING: before and after analysis	EVALUATION/ MONITORING: alternatives analysis
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity																P	S		Q A	Q A		A	O	O
ENVIRONMENT	Decrease overall impacts to the environment and resources																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, PMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance	[3] -18%–3.7% [11] -72.43 tons/year, HC -273.82 tons/year, CO 133.60 tons/year, NOx	P	P	S	S	S													Q A	Q A		A	O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments	[3] 50%–75% approve toll lanes 30%–75% approve variable tolls 45%–75% approve selling capacity to SOVs [9] 53% report willingness to pay toll <$2.00										P								A	A				
ORGAN. EFFICIENCY	Minimize costs	• Cost for construction (per lane-mile, VMT, PMT)	[11] $2 mil annually, direct connector ramps	P				P	S								P				A O				O	O
ORGAN. EFFICIENCY	Minimize costs	• Vehicle operating costs (per lane-mile, VMT, PMT)	[11] $4 mil annually, toll/credit transaction costs	P				P	S							P			S		Q A				O	O
ORGAN. EFFICIENCY	Minimize costs	• Cost-benefit measures	[1] 8.2–11.9 B/C [11] 5.6 B/C	P	P		S									P	P	S	S		A				O	O
ORGAN. EFFICIENCY	Maximize revenue	• Toll revenue	[11] $13.79 mil annually																	P	M Q A			A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] DeCorla-Souza (2002), [2] Berg (1999), [3] Sullivan (2000), [4] Supernak et al. (2003a), [5] Supernak et al. (2003b), [6] Hickman et al. (2000), [7] Swenson et al. (1999), [8] Burris and Swenson (2000), [9] He et al. (2001), [10] PBQD (2005), [11] DeCorla-Souza (2002).

Similar to HOV lanes, value-priced and HOT lane performance depends upon the ability to encourage mode shift to higher occupant vehicles through reduced travel times, increased travel reliability, and enhanced safety. This mode shift is reflected in increases in person throughput and average vehicle occupancies. Unlike HOV lanes, value-priced and HOT lanes also benefit from revenue generation and rely on achieving a temporal shift to encourage eligible toll vehicles (SOVs or HOVs not meeting standard eligibility requirements) (1) to pay a high-rate toll to take advantage of the potential travel-time savings during peak periods and/or (2) to alter trip times to take advantage of lesser tolls during the shoulders of the peak periods when additional excess capacity is available (i.e., peak spreading). One challenge is separating the performance of the value-priced and HOT lane effects from standard HOV lane effects.

EXCLUSIVE LANES

Exclusive lanes can be either passenger-focused or freight-focused. Both applications are described below.

Collective Guidelines - Passenger Focus

As early as the 1970s, exclusive busways were implemented on Shirley Highway in the Washington, D.C., area, El Monte Freeway in Los Angeles, the I-495 approach to the Lincoln Tunnel in New Jersey, California Highway 101 in the San Francisco metropolitan area, and a separate right-of-way in Pittsburgh. With the exception of the I-495 lane in New Jersey and the Pittsburgh busway, the early highway exclusive bus lanes have all since been converted to HOV lanes, with carpools being the predominant users (FTA 2002). Recently, the implementation of exclusive busways has resurged under the Federal Transit Administration's Bus Rapid Transit (BRT) Demonstration Program.

BRT combines exclusive lanes to reduce congestion delay, traffic signal priority to reduce signal delay, low floor buses and high boarding platforms to reduce boarding delay, prepaid/electronic fare payment to reduce fare collection delay, and limited stops to increase average speed. Of interest to this investigation is the impact of exclusive lanes on overall system performance monitoring and evaluation.

Two documents of significance were developed in support of or as a result of the BRT Demonstration Program: (1) *Evaluation Guidelines for BRT Demonstration Projects* (FTA 2002) and (2) *Characteristics of Bus Rapid Transit for Decision-Making Experience with BRT System Performance* (FTA 2004). The first document provides consistent guidelines for setting related goals and objectives, defining performance measures, identifying and collecting supporting data, and analyzing and reporting performance findings. The second document summarizes the observed performance of a number of BRT systems currently in the demonstration phase. The first document is described here; the second is described later in this document under *Site-specific Findings.*

With respect to goals and objectives, the BRT Program is consistent with FTA Strategic Plan goals of improving mobility and accessibility and providing efficient transportation. Specific objectives of the program include:

- improving bus speeds and schedule adherence;
- increasing ridership due to improved bus speeds, schedule adherence, and convenience;
- minimizing the effect of BRT on other traffic and local businesses;
- isolating the effect of each BRT feature on bus speed and other traffic;
- assessing the benefits of ITS technology applications to the demonstration; and
- assessing the effect of BRT on land use and development (FTA 2002).

Although not explicitly stated as a program objective, of concern to any organization involved in providing bus service is getting the most benefit for the traveling public within the confines of their limited resources (tax dollars, operating subsidies, and revenues) (FTA 2002).

To address each of the objectives above, Table 38 summarizes the recommended performance measures for BRT monitoring and evaluation. FTA (2002) also considers these performance measures in terms of BRT component. For this investigation, which considers exclusive lanes to be a managed lane strategy, performance measures related to express rights-of-way (busways and exclusive bus lanes) are of most interest (see Table 39). Measures appropriate for assessing the impacts of express rights-of-way include all phases of travel time, transit ridership, bus speed, and passenger loads on BRT and parallel routes.

Table 38. Recommended BRT Performance Measures (FTA 2002).

GOAL AREA	PERFORMANCE MEASURE
Travel Times and Schedule Adherence	Total travel time includes access, wait, transfer, in-vehicle (when the vehicle is moving, time stopped at traffic signals, and dwell time at bus stops), and egress time. Schedule adherence or reliability of service can be seen either as an independent parameter or as a component of the measurement of travel time.
Ridership	Travel time is perhaps the single most important determinant of transit ridership levels (along with out-of-pocket costs such as fares or parking costs avoided).
Impacts on Other Traffic	Giving transit priority in terms of street design, traffic signals, or merging may increase travel times for other road users. Eliminating on-street parking may improve travel for all road users.
Land Use, Urban Design, and Environmental Impacts	Extent to which transit-supportive land use policies can be instituted along with changes in transit service.
Transit System Image and Public Perception	Improved image is ultimately measured by increased ridership, but public surveys can also indicate the success of marketing and promotional efforts.
Costs, Productivity, and Cost-effectiveness	Reductions in travel time allow transit agencies to provide the same amount of service with fewer operator and vehicle hours.

Table 39. Recommended BRT Performance Measures for Busways and Exclusive Bus Lanes (FTA 2002).

PERFORMANCE MEASURE	BUSWAY	EXCLUSIVE BUS LANE
Average and maximum bus speed	✓	✓
Travel time by trip phase	✓	✓
Ridership	✓	✓
Passenger loads on BRT and parallel routes	✓	✓
Passenger satisfaction	✓	✓
Improvements in transit image	✓	✓
Accidents	✓	✓
Capital and operating costs	✓	✓

With respect to travel time, the *Transit Capacity and Quality of Service Manual – 2nd Edition* [Transit Cooperative Research Program (TCRP) 2003] provides estimated average speeds of buses as a function of three variables:

- type of running way (e.g., busway, arterial street bus lane, or mixed traffic);
- average stop spacing; and
- average dwell time per stop.

Tables 40 through 43 summarize the estimated average bus speeds given these factors.

Table 40. Estimated Average Bus Speeds on Busways or Exclusive Freeway HOV Lanes: Assumes 50 mph Top Running Speed of Bus in Lane (TCRP 2003).

AVERAGE STOP SPACING	AVERAGE DWELL TIME (per stop)				
	0 sec.	15 sec.	30 sec.	45 sec.	60 sec.
0.5 mi.	36 mph	26 mph	21 mph	18 mph	16 mph
1.0 mi.	42 mph	34 mph	30 mph	27 mph	24 mph
1.5 mi.	44 mph	38 mph	35 mph	32 mph	29 mph
2.0 mi.	46 mph	41 mph	37 mph	35 mph	32 mph
2.5 mi.	46 mph	42 mph	39 mph	37 mph	35 mph

Table 41. Estimated Average Bus Speeds on Dedicated Arterial Bus Lanes (TCRP 2003).

AVERAGE STOP SPACING	AVERAGE DWELL TIME (per stop)					
	10 sec.	20 sec.	30 sec.	40 sec.	50 sec.	60 sec.
0.10 mi.	9 mph	7 mph	6 mph	5 mph	4 mph	4 mph
0.20 mi.	16 mph	13 mph	11 mph	10 mph	9 mph	8 mph
0.25 mi.	18 mph	15 mph	13 mph	11 mph	10 mph	9 mph
0.50 mi.	25 mph	22 mph	20 mph	18 mph	16 mph	15 mph

Table 42. Estimated Average Bus Speeds in General Purpose Traffic Lanes (TCRP 2003).

AVERAGE STOP SPACING	AVERAGE DWELL TIME (per stop)					
	10 sec.	20 sec.	30 sec.	40 sec.	50 sec.	60 sec.
0.10 mi.	6 mph	5 mph	5 mph	4 mph	4 mph	3 mph
0.20 mi.	9 mph	8 mph	7 mph	6 mph	6 mph	5 mph
0.25 mi.	10 mph	9 mph	8 mph	7 mph	7 mph	6 mph
0.50 mi.	11 mph	10 mph	10 mph	9 mph	9 mph	8 mph

Table 43. Busway and Freeway Bus Lane Speeds by Station Spacing (TCRP 2003).

STATION SPACING	STOPS PER MILE	SPEEDS	
		20-Second Dwell	30-Second Dwell
0.25 mi.	4.0	18 mph	16 mph
0.50 mi.	2.0	25 mph	22 mph
1.00 mi.	1.0	34 mph	31 mph
1.50 mi.	0.7	42 mph	38 mph
2.00 mi.	0.5	44 mph	40 mph

Note that the estimated average bus speeds on busways or exclusive freeway lanes is typically more than twice that of average speeds of buses traveling on arterial street bus lanes or in general purpose traffic lanes. These estimates are confirmed through site-specific observations of the demonstration BRT systems described later in this document.

Rider surveys may help gauge satisfaction with BRT service compared to other modes including automobile and regular transit service and improvements in the image and visibility of BRT and transit in general.

Express rights-of-way have higher capital costs, typically requiring the acquisition of land and rights-of-way, as well as the construction of the bus lanes themselves. Exclusive bus lanes may require considerable road and curb modifications, construction of bus stops, information kiosks, and other passenger amenities, signage, and marketing. Operating costs can be estimated based on vehicle hours. The net change in operating costs should be considered after accounting for any reductions in service on parallel routes.

Site-specific Findings - Passenger Focus

Using the goals and objectives and related performance measures outlined above, BRT performance was observed for 10 systems across the nation. These evaluation findings related to travel time and schedule adherence (reliability); ridership; impacts on other traffic; transit system image and public perception of transit service; safety; and costs, productivity, and cost effectiveness, described in the *Characteristics of Bus Rapid Transit for Decision-Making Experience with BRT System Performance* (FTA 2004), are summarized below.

In general, BRT experience suggests that travel-time savings is on the order of 25 to 50 percent for recently implemented BRT systems. Systems with more exclusive running ways generally experienced the greatest travel-time savings compared to the local bus route. Exclusive transitway projects operated at a travel time rate of 2 to 3.5 minutes per mile (between 17 and 30 mph) while arterial BRT projects in mixed-flow traffic or designated lanes operated between 3.5 and 5 minutes per mile (between 12 and 17 mph).

Performance in reliability demonstrated a similar pattern. Of the systems that operate on dedicated or exclusive lanes, the “Ratio of Maximum Time to Unconstrained Time” ranges between a high of 1.26 (North Las Vegas MAX) to a low of 1.00 (LYMMO, Miami Local, Miami Busway MAX and the South Busway in Pittsburgh). For systems that operate along mixed-flow lanes, this ratio was typically higher, ranging from 1.17 for the Metro Rapid Vermont line to 1.54 for the Metro Rapid Ventura line, both in Los Angeles. Systems with a ratio of 1.00 indicate that travel times are not impacted by prevailing traffic conditions.

There have been significant increases in transit ridership in virtually all corridors where BRT has been implemented. Ridership increases have come from passengers formerly using parallel service in other corridors, as well as passengers new to transit. Ridership gains of between 5 and 25 percent are common. To date, none of the BRT systems in the U.S. have operated at their maximum capacity, providing room to expand by operating larger vehicles, higher frequencies, or both.

BRT passengers generally had higher customer satisfaction and rated service quality higher for BRT systems than for their parallel local transit services (FTA 2004).

With respect to operating cost efficiency, experience shows that corridor performance indicators (such as passengers per revenue hour, subsidy per passenger mile, and subsidy per passenger) improve with the introduction of BRT. Furthermore, travel-time savings and higher reliability enable transit agencies to operate more vehicle miles of service for each vehicle hour operated.

Data measuring the difference in safety of BRT systems compared with the rest of the respective region's transit system have largely not been collected; drawing conclusions about the efficacy of BRT elements in promoting safety is therefore premature in all but a few instances.

While these general BRT performance findings are of interest, this investigation primarily focuses on the performance of exclusive lanes (i.e., fully grade-separated exclusive transitways, at-grade exclusive transitways, or, to a lesser extent, designated (reserved) arterial lanes) as part of an overall BRT system. As such, the remainder of this section considers only those BRT systems that utilize at-grade or grade-separated exclusive lanes including:

- LYMMO, Orlando, Florida;
- MAX (South Dade) Busway, Miami-Dade, Florida; and
- Busways (West, East, and South), Pittsburgh, Pennsylvania;

and, to a lesser extent, systems that operate on a combination of exclusive (dedicated) and mixed-flow lanes including:

- MAX, Las Vegas, Nevada;
- Silver Line, Boston, Massachusetts; and
- RAPID, Phoenix, Arizona.

Comparative performance-related findings, as well as key system descriptors, are summarized in Tables 44 and 45 for each of the respective system types. Additional findings are included below.

Table 44. At-Grade and Grade-separated Exclusive Lane BRT System Characteristics and Performance (FTA 2004).

		ORLANDO LYMMO	MIAMI MAX Busway	PITTSBURGH East Busway	PITTSBURGH South Busway	PITTSBURGH West Busway
Running Way	At-grade Excl. Lanes	3.0 mi.	8.0 mi.			
	Separated Excl. Lanes			8.7 mi.	4.3 mi.	4.6 mi.
	Guidance			8.7 mi.		
	Passing Capability		Bus pullouts	Passing lanes	Adjacent mixed-flow lane	
Stations	Type	Enhanced shelter	Designated station			
	Platform Height	Standard curb				
	Platform Length	2 veh.	3 veh	2-3 veh.		
	Access	Pedestrian focus	Park and Ride Lots			
Vehicles	Type	Standard articulated, minis		Conventional standard and articulated		
	Styling Amenities	Specialized livery				
	Propulsion System		Internal Combustion Engine (ICE) -diesel			
Fares	Process	N/A	Pay-on-board			
	Media	N/A	Cash, magnetic stripe	Cash and paper		
	Structure	Free	Flat	Differentiated		
ITS	Vehicle Priority		Transit Signal Priority (TSP)			
	Driver Assist/Auto.			Collision warning		
	Operations Management	Automatic Vehicle Location (AVL)				
			Adv. communication			
	Passenger Information	Station, Internet				
			Personal Digital Assistant (PDA), Vehicle			
Service Plan	Route Length	3 mi.	8.0 mi.	9.1 mi.[1]	4.3 mi.	5.0 mi.[1]
	Route Structure	All-stop		Integrated network		
			Limited express			
	Service Span	All day				
	Service Frequency	5 min	10 min	12 min	12 min	12 min
Travel Time	Max. peak hour (PH) end-to-end	20	25	20	9	17
	Uncong. end-to-end	20	25	18	9	14
	PH minutes/mile	6.67	3.13	2.20	2.09	3.40
	Uncong. minutes/mile	6.67	3.13	1.98	2.09	2.80
	Reduction - local	0%				
	Reduction - system		35%	52%	55%	26%
	Reduction - by agency					
	Customer perception					85% report reduction, avg. 14 min
Reliability	Max/min run time	1.00	1.00	1.11	1.00	1.21
	Coef. of variation			Reduced 18.8% to 10.2%		
	Customer perception					68% perceive improvement
Ridership	Existing routes-before	1,750				3,700
	Existing routes-after					3,300
	New BRT routes	5,000	9,395			5,400
	Total ridership	5,000	9,395	30,000	13,000	8,700
	Change in ridership	186%				135%
	Attractiveness	1,750		11% used car		34% used car

[1] The Pittsburgh West Busway includes 0.4 miles of mixed-flow operations along the East and West Busways; the effects of this mixed-flow operation of overall facility performance were assumed to be negligible.

Table 45. Combined Mixed Flow and Designated Lane BRT System Characteristics and Performance (FTA 2004).

		LAS VEGAS	BOSTON	PHOENIX			
		North LV MAX	Silver Line	RAPID I-10 East	RAPID I-10 West	RAPID SR-51	RAPID I-17
Running Way	Mixed-Flow Lanes	2.9 mi.	0.2 mi.	6.5 mi.	4.8 mi.	12.3 mi.	8.0 mi.
	Designated Lanes	4.7 mi.	2.2 mi.	14.0 mi.	8.0 mi.	10.3 mi.	11.5 mi.
	Guidance	Precision dock					
	Passing Capability	Adjacent mixed-flow lane		Bus pullouts			
Stations	Type	Designated station	Enhanced shelter				
	Platform Height	Level platform	Standard curb				
	Platform Length	1 veh.					
	Access	Pedestrian focus					
Vehicles	Type	Specialized BRT					
	Styling Amenities	Specialized livery		Composite and styling			
		Large windows					
		Internal bike racks					
	Propulsion System	Diesel-electric hybrid		Liquefied Natural Gas (LNG)			
Fares	Process	Proof-of-payment	Pay on board				
	Media	Cash, magnetic stripe					
	Structure	Flat		Differentiated			
ITS	Vehicle Priority	TSP					
	Driver Assist/Auto.	Precision docking		Collision warning			
	Operations Management	Advanced communication					
		AVL					
			CAD				
	Passenger Information	Station, Internet					
		Telephone		Vehicle, PDA			
Service Plan	Route Length	7.6 mi.	2.37 mi.	20.5 mi.	13 mi.	19.25 mi.	19.5 mi.
	Route Structure	Single route	All-stop	Express			
	Service Span	All day		Weekday peak hour only			
	Service Frequency	12 min	4 min	10 min			
Travel Time	Max. PH end-to-end	32	9.6	37	34	48	52
	Uncong. end-to-end	28	9.3				
	PH minutes/mile	4.21	4.05	1.80	2.62	2.49	2.67
	Uncong. Minutes/mile	3.68	3.92				
	Reduction - local	35%	26%				
	Reduction - system						
	Reduction - by agency		29%				
	Customer perception		73.2% above avg. or excellent				
Reliability	Max/min run time	1.14	1.03				
	Coef. of variation			90%	100%	100%	100%
	Customer perception		65% above avg. or excellent				
Ridership	Existing routes-before		7,627				
	Existing routes-after						
	New BRT routes		14,105				
	Total ridership		14,105	607	435	533	797
	Change in ridership		85%				
	Attractiveness		25.1% used other modes				

Florida

LYMMO, Orlando. By providing high-quality, frequent, and reliable transportation for downtown employees, visitors, and residents, LYMMO has increased accessibility to public transit and spurred development along its route. LYMMO has a reliability ratio (i.e., ratio of maximum time to unconstrained time) of 1.00, indicating that travel times are not impacted by prevailing traffic conditions. Likely as a direct or indirect result, ridership has increased 186 percent.

LYMMO operates on an at-grade dedicated route for the entire 3.0-mile length. The total capital cost for the LYMMO BRT in Orlando, Florida, was $21 million, or $7 million per route mile. The annual operating cost for LYMMO is approximately $1 million.

MAX (South Dade) Busway, Miami-Dade. The MAX (South Dade) Busway also operates on an at-grade dedicated route for its entire 8.0-mile length. Like LYMMO, MAX has a reliability ratio (i.e., ratio of maximum time to unconstrained time) of 1.00, indicating that travel times are not impacted by prevailing traffic conditions. MAX also reports a 35 percent travel time reduction when compared system wide.

The total capital cost for Phase I of the South Miami-Dade Busway was $42.9 million ($5.0 million per mile) with $17 million going to the purchase of dedicated right-of-way to build the actual busway. Metro-Dade Transit (MDT) uses smaller 30-foot buses on the busway to keep operating costs to a minimum. The use of the smaller mini-buses has greatly reduced the operating cost per revenue hour of busway operation.

Since opening in 1997, many serious collisions between BRT vehicles, motorists, and pedestrians have occurred at intersections along the MAX Busway. In response, MDT and Miami-Dade County installed extensive signage and signalization to deter such crossings and revised operating procedures, requiring slow procession of busway vehicles through busway intersections to minimize the risk of collision.

Pennsylvania

Busways (East, South, and West), Pittsburgh. Three grade-separated busways operate in the greater Pittsburgh area. The Martin Luther King Jr. (East) Busway is 8.7 miles in length and the South and West Busways are 4.3 and 4.6 miles in length, respectively. The West Busway includes 0.4 miles of mixed-flow operations; the effects of this mixed-flow operation on performance were assumed to be negligible over the length of the facility.

The Martin Luther King Jr. East Busway serves travelers between downtown Pittsburgh and eastern suburbs. To assess busway performance related to travel-time savings, the time required for walk access to service, downtown circulation, and line-haul travel were calculated for six key downtown destinations for both the a.m. peak and the p.m. peak. In all cases in the a.m. peak, the line-haul travel time decreased by an average of 5 or 6 minutes, while downtown circulation time decreased for four out of six locations. Overall, total travel time decreased by an average of 8 minutes out of total travel times of 31 to 34 minutes. Travel time savings for trips during the a.m. peak were between 13 and 42 percent. p.m. peak travel-time savings were not as notable; about 3.5 minutes on average. The East Busway averages 1.98 minutes per mile, which is among the lowest among the BRT demonstrations and significantly lower than that of BRT systems that operate within a mixed-flow traffic environment.

Comparably, the South Busway averages 2.09 minutes per mile. The South Busway provides a 55 percent travel-time savings over the average system-wide minutes per mile for all Port Authority fixed-route service. The West Busway reports the lowest travel time benefits; providing a 26 percent travel-time savings over the system average. Eighty-five percent of survey respondents reported a travel time reduction averaging 14 minutes per trip along this route.

Despite notable travel-time savings across all facilities, only the South Busway reports a reliability ratio (i.e., ratio of maximum time to unconstrained time) of 1.00, indicating that travel times are not impacted by prevailing traffic conditions. Reported reliability ratios for the East and West Busways are 1.11 and 1.21, respectively, with a recent reduction in travel time variability from 18.8 percent to 10.2 percent reported for the East Busway. Also interesting to note is that 68 percent of survey respondents perceive an improvement in reliability along the West Busway despite no reported improvements and the highest (worst) reported reliability ratio.

Ridership along the West Busway has increased by 135 percent, with 34 percent of passengers reporting a mode shift from their personal automobile. For the East Busway, the reported mode shift from personal automobiles was 11 percent.

To investigate agency efficiencies, an analysis performed by Port Authority Transit (now Port Authority of Allegheny County) assigned operating costs to transit trips and calculated operating cost parameters for different types of routes (see Table 46), factoring in these travel time effects (i.e., higher speeds allow more vehicle-miles of service to be operated with the same number of vehicle hours, which drives major operating costs such as labor costs).

With respect to cost effectiveness, new routes on the East Busway outperform both diverted routes and all other routes in the system. Diverted routes demonstrate the lowest cost effectiveness since they tend to generate demand further below capacity than other routes. New routes and diverted routes on the East Busway operate with higher operating cost efficiencies with respect to capacity-focused measurements (e.g., per seat-mile and per peak seat-mile). The higher cost of operating per vehicle-miles for new routes can be attributed to the fact that those routes are operated with articulated vehicles. The comparison of vehicle-miles per vehicle hour shows that routes on the East Busway are able to generate between 37 and 70 percent more vehicle-miles from each vehicle hour (FTA 2004).

Comparatively, the West Busway demonstrated the performance measures for operating cost efficiency and cost effectiveness shown in Table 47.

Table 46. Operating Cost per Service Unit by Type of Route (1983 Dollars, FTA 2004).

PERFORMANCE MEASURE		NEW ROUTES	DIVERTED ROUTES	ALL OTHER ROUTES IN SYSTEM
Cost Effectiveness	Per Passenger Trip	$0.76	$1.95	$1.27
	Per Peak Passenger Trip	$1.32	$3.19	$3.09
	Per Passenger Mile	$0.15	$0.37	$0.24
	Per Peak Passenger Mile	$0.27	$0.60	$0.58
Cost Efficiency	Per Seat Mile	$0.06	$0.06	$0.07
	Per Peak Seat Mile	$0.12	$0.09	$0.16
	Per Vehicle Mile	$3.61	$2.58	$3.26

Table 47. West Busway Operating Cost Efficiency in Aggregate and by Route Type (1983 Dollars, FTA 2004).

OPERATING COSTS	
Per vehicle revenue mile	$6.40
Per vehicle revenue hour	$81.90
Per passenger mile	$0.65
Per unlinked passenger trip	$2.73
ROUTE TYPE	
New routes	15.8 vehicle-miles per hour
Routes diverted to East Busway	19.6 vehicle-miles per hour
Other Routes in System	11.5 vehicle-miles per hour

Data from Pittsburgh suggest that BRT operations on exclusive transitways have significantly fewer accidents per unit (vehicle mile or vehicle hour) of service than conventional local transit operations in mixed traffic. Bus service in the east corridor has experienced a 30 percent reduction in all accidents but a 6 percent increase in passenger accidents after the implementation of the East Busway.

Nevada

MAX, Las Vegas. MAX operates along the North Las Vegas Boulevard corridor; a low-density corridor extending from downtown Las Vegas to the north. Its total length of 7.6 miles comprises 2.9 miles of operation in mixed-flow traffic and 4.7 miles of operation on dedicated (exclusive) arterial lanes. The MAX system was inaugurated in the summer of 2004, precluding an extensive performance review. Early results do indicate a 35 percent travel-time savings improvement over other local routes and a reliability ratio of 1.14, which is surprisingly good for arterial/mixed-flow operations.

Massachusetts

Silver Line, Boston. Phase I of the Silver Line was developed along the Washington Street corridor, the primary link between downtown Boston and towns to the south and west. This system is short in length, operating for 2.2 miles on dedicated arterial lanes and for 0.2 miles in mixed-flow lanes.

The Silver Line reports a 29 percent travel-time savings improvement over agency-wide averages and a reliability ratio of 1.03. This high level of reliability is likely attributable to the short route length of the system. Customer satisfaction for the system is high, with 73.2 percent and 65 percent of customers rating travel time and reliability performance, respectively, as above average or excellent. This high customer satisfaction has resulted in a 185 percent increase in ridership, with 25.1 percent of passengers reporting a mode shift from alternative modes to the Silver Line.

Arizona

RAPID, Phoenix. Operating over significantly longer route segments ranging from 13 to 20.5 miles, the RAPID system includes routes along I-10 East, I-10 West, SR-51, and I-17 in the greater Phoenix area. Each of these routes comprises dedicated lane operation and mixed-flow operation; with approximately half of the mileage occurring in each operating environment per route. Little performance data have been reported for this system; the first two RAPID routes opened in 2003.

Collective Guidelines - Freight Focus

Shifting focus to freight movement, exclusive truck lanes operate in much the same fashion as exclusive bus lanes but with different objectives related to traffic flow and safety. Limited collective guidance was found to evaluate and monitor the performance of exclusive truck lanes, largely because of the lack of exclusive truck lane facilities in operation. Hence, any guidance documents that were uncovered related more toward the process of determining feasibility of exclusive truck facilities.

Mason et al. (1986), as a rule of thumb, suggest that separate truck lanes may be feasible in areas where truck volumes exceed 30 percent of vehicular traffic, peak-hour volumes exceed 1800 vehicles per lane-hour, and off-peak volumes exceed 1200 vehicles per lane-hour.

Taking this to the next level, FHWA (1990) developed a method and computer program called EVFS (exclusive vehicle facilities software) to help determine the economic feasibility of separating light and heavy vehicles on interstate and other controlled-access highways. EVFS calculates the net present worth (NPW), benefit-cost ratio (B/C) and other facility performance measures for various lane configurations that designate existing lanes or provide additional lanes exclusively for trucks or passenger vehicles.

In addition to the NPW and B/C for each alternative being considered, other potential benefits include:

- travel-time savings due to faster traffic flow;
- vehicle operating cost savings due to improved traffic flow;
- injury and property damage savings due to fewer severe crashes; and
- travel delay savings due to fewer blockages causing accidents.

Cost components include engineering and construction, right-of-way acquisition and demolition, and periodic pavement resurfacing.

Along I-81 in Virginia, Hoel and Vidunas (1997) utilized EVFS to demonstrate application of the program. A number of factors contribute to the feasibility of exclusive lanes. Although no factor predominates, EVFS gives more weight to traffic volume, vehicle mix percentage, crash rates, and maintenance and construction costs than to other factors. EVFS does not differentiate among lanes (i.e., inside, middle, or outside) to which restrictions are applied and is unable to effectively analyze exclusive lane alternatives in which a barrier separates vehicle types.

Most recently, Samuel et al. (2002) considered the feasibility of truck tollways. In doing so, investigators developed an analysis methodology consisting of three main components:

1. **Pavement Design.** Design pavements for the various scenarios of truckway usage, enabling realistic estimation of initial investment and providing input to pavement deterioration models.
2. **Productivity Analysis.** Quantify the impact that the truckway system would have upon the productivity of truck fleets, measured by the resulting changes in operating costs. Results provide information about the range of tolls that could be levied from trucks using the truckway system.
3. **Feasibility Analysis.** Estimate the likely feasibility of the proposed toll truckway concept using modeled pavement deterioration and corresponding estimated road user costs. The feasibility analysis considers two major facets: the overall economic feasibility of the project from the system-wide point of view and the private (financial) feasibility of the project from the standpoint of a private toll truckway developer/operator.

For details about this analysis process, refer to Samuel et al. (2002). Application of this analysis method for a variety of truck tollway scenarios resulted in the following findings. Intercity toll truckways would be economically and financially feasible across a wide range of possible scenarios. Specifically, under most scenarios, the addition of toll truckways to intercity routes would be economically beneficial with strong positive net present value. Similarly, realistic toll rates would produce positive and often commercial rates of return on investment over a wide range of scenarios, which suggests that toll truckways could be self-funding enterprises.

This analysis should be considered conservative in that (1) it is based only on the types of vehicles currently in use and not on larger and more productive combinations that might be developed to take better advantage of the toll truckways' capabilities; with significantly higher productivity gains, there should be a willingness to pay higher tolls to obtain those gains; and (2) its financial feasibility analysis relied on toll levels in many cases equivalent to far less than half the cost savings that would be realized by trucking firms using the toll truckways.

Utilizing this same analysis procedure and building upon the earlier work of Samuel et al. (2002), Holguin-Veras et al. (2003) considered the effects of exclusive truck lanes in combination with high gross weight limits and sizes for trucks using the system, financing tolls levied on trucks using the system, and providing gas tax rebates for exclusive lane-miles traveled. The feasibility study, complemented by a sensitivity analysis on key variables, strongly suggests that at relatively low traffic levels (20,000 vehicles per day), exclusive lane implementation has a beneficial economic effect. As traffic increases, so does the benefit. As determined by the balance between revenue stream and the annualized exclusive lane building and operating costs, the financial feasibility analysis indicates that tolls between $0.25 and $0.50 per kilometer yield a rate of return higher than the opportunity cost of the capital (estimated at 6 percent).

Site-specific Findings - Freight Focus

Consistent with the reasoning behind the dearth of collective guidance for exclusive truck lane evaluation and monitoring, according to *NCHRP Synthesis 314 Strategies for Managing Increasing Truck Traffic* (Douglas 2003), exclusive lanes for trucks are infrequent. A national survey conducted as part of this effort asked respondents whether the following types of roadway facilities have been studied or implemented: dedicated roads for trucks or commercial vehicles, special-use lanes for trucks or commercial vehicles, truck climbing lanes, and dedicated truck ramps.

Climbing lanes for trucks are a common practice; more than 75 percent (20 of 26) of the states responding to the survey have climbing lanes. The other types of roadway facilities are much less common. Approximately 20 percent of states are developing special-use lanes (6 of 26) or dedicated ramps (5 of 24), and only 1 state of 25 reports approval of a dedicated road for trucks; the NYSDOT has allocated $11 million for a new truck-only route along Edgewater Road between the southbound Sheridan Expressway and the Hunts Point Market. Not reported as part of this survey, Massachusetts implemented the South Boston Bypass as a dedicated road for commercial vehicles, but researchers recovered no information describing this route.

Instead, the majority of exclusive lane facilities for trucks are short in length and intended to improve access to ports, improve processing at border crossings, or improve roadway operations at locations where merging, diverging, and weaving is problematic. These types of facilities are described in *Mixed-flow Separation/Bypass Lanes* later in this document.

Three responding states have considered but rejected special-use lanes, and one of these three also rejected dedicated roads. The factors behind the decisions vary, but public opinion plays a significant role when special-use facilities are considered.

Because of limited implementation, the majority of site-specific studies conducted (i.e., Washington, California, Florida, Georgia, and the I-35 multi-state corridor) have considered the feasibility of exclusive truck lanes and simulated impacts; no implementations provide observed evaluation results. In addition, a number of feasibility studies are currently under way, including Virginia along I-81 and the I-69 multi-state corridor.

Washington

A simulation study conducted in Washington (Trowbridge et al. 1996) considered the effects of both exclusive truck lanes and the use of existing HOV lanes by trucks along several routes in the greater Seattle area. The study considered operational impacts, economic impacts, safety impacts, and pavement deterioration rates, as well as public opinion.

Potential benefits from exclusive truck lanes include:

- a reduction in truck travel times, improving freight movement efficiency;
- more predictable travel times, allowing expansion of just-in-time delivery options;
- an improvement in domestic and international competitiveness; and
- maintenance of consumer goods pricing.

Benefits for other users of the facility include:

- an improvement in capacity for the facility by removing trucks from the general-purpose lanes;
- a reduction in truck idle time due to congestion, which reduces fuel consumption and improves air quality;
- an improvement in safety (a reduction in the number of crashes and severity) by grouping vehicles of similar characteristics in a single lane;

- a reduction in incident impacts (fewer lanes blocked, easier to access and clear) by concentrating trucks in an outside lane;
- a reduction in pavement rehabilitation costs by concentrating heavy loads in a single lane (i.e., only a single lane would have to be rehabilitated and this lane could eventually be reconstructed to provide additional strength); and
- a more comfortable driving environment for those intimidated driving near trucks.

The study found that reserved capacity strategies for trucks would offer nearly $10 million in annual travel-time savings for the trucking industry in the Seattle region. The impact on individual trips would be small; about 2.5 minutes saved per average trip (less than 8 percent savings in trip travel time). The biggest impact of truck reserved capacity strategies is in the travel-time savings they would create for single-occupant vehicles; almost $30 million per year. This travel-time savings would be an artifact of the current underutilization of HOV lanes in the Seattle area and not necessarily a virtue of reserved-capacity strategies. The difference in travel times between the reserved capacity strategy that adds trucks to the existing HOV lanes and the one that adds an exclusive truck lane are insignificant, providing little justification for construction of an exclusive lane.

The effect of reserved capacity strategies on safety is a function of whether the lanes are on the left or right side. Left-side lanes may increase side-swipe accidents, whereas right side lanes may increase other types of accidents because of interactions with merging traffic. Sight distances and operation of general-purpose lanes would generally improve.

Reserved capacity strategies would accelerate pavement deterioration in the reserved lane. This expense is offset by the reduction in pavement deterioration rates in the general-purpose lanes. The net effect may be an increase in capital expenditures; this increase would likely be very small.

The public opinion survey showed considerable resistance to reserved capacity strategies for trucks. This resistance is not unlike that encountered when HOV lanes were first considered. Careful marketing and public education could ease the reception.

California

Similarly, Taylor (2001) completed a feasibility study on exclusive lanes for commercial trucks along State Route 60 (SR-60), from I-710 to I-15, a distance of approximately 38 miles.

This freeway, serving intermodal freight yards and bridging between the Ports of Long Beach/Los Angeles and inland areas, currently carries a daily truck volume of more than 20,000 in some locations, projected to more than double by 2020. SR-60 is identified in the association's adopted 2001 Regional Transportation Plan as one of four highways planned to include exclusive truck lanes by 2025.

In the current Regional Transportation Plan (RTP) for Southern California, the Southern California Association of Governments (SCAG) identifies dedicated truck lanes as means to more efficiently keep goods movement flowing smoothly, improve overall mobility along the freeway, and improve traffic safety and air quality issues.

Three main strategies were considered: (1) allowing trucks to share the HOV lanes during limited time periods, (2) adding truck lanes to the freeway at grade, and (3) adding lanes above the freeway grade. The shared HOV option was dropped due to a number of barriers including legal and funding obstacles.

The study recommended combining the two remaining strategies, with at-grade truck lanes built where feasible and above-grade mixed-flow lanes (trucks would operate at grade for safety) built where right-of-way acquisition would be difficult. Above-grade lane sections should be kept to a minimum due to safety and operational consideration, as well as higher construction costs.

The study also evaluated opportunities for revenue collection through tolling. At a capital development cost of approximately $16.5 billion, the study showed that a per-mile toll ranging from $0.38 to $0.80 and averaging $0.56 over a 30-year financing period would be sufficient to totally fund the development and operation of this system. Additional studies of key regional goods movement corridors are under way for I-710 and I-15, along with a study of the Eastern Gateway Freeway Corridor.

Florida

With a directed focus on areas where trucks have a significantly negative impact on safety and congestion, Reich et al. (2003) considered the feasibility of separating large trucks from the traffic mix. Researchers constructed several geographic information system (GIS) models to identify "hot spots" based on truck crashes, truck volume and percent, and level of service. Both rural and urban locations were considered, as each scenario presented a different set of challenges. Lastly, researchers assessed the feasibility of countermeasures for each site. Researchers determined that most of Florida's interstate system was suitable for exclusive truck facilities, with the most appropriate areas having sufficient available right-of-way.

Georgia

Most recently, Parsons, Brinkerhoff, Quade, and Douglas (PBQD 2005) completed a feasibility study in Atlanta that considers both high-occupancy toll and truck-only toll (TOT) lanes. With respect to TOT lanes, the stated facility objectives are to:

- Improve safety - the inherent safety problem created by the size disparity between trucks and other automobiles and danger of traveling side by side at high speeds and in congested areas is avoided.
- Improve efficiency - freight could travel more efficiently without placing a strain on the already limited federal, state, and local highway funds.
- Generate revenue - tolls provide an additional source of revenue to pay for transportation improvements.

The overall goal is to manage heavy-duty vehicle flow in transportation corridors by maximizing the utilization of transportation infrastructure in order to improve productivity and enhance safety.

The project study area included all limited-access facilities in the 13-county Atlanta region. This study examined three TOT lane alternative concepts (scenarios):

- **A1 Major Truck Corridors.** Along two of the most promising corridors in the region, two TOT lanes would be constructed in each direction, in addition to HOV lanes, with access provided to the local road network at appropriate locations.
- **A2 Service to Deliveries.** Assuming that the TOT lanes of A1 are in place, the current HOV lanes inside I-285 would additionally be reserved for light-duty commercial vehicles willing to pay a fee during the midday.
- **A3 Regional TOT Network**. All existing and proposed HOV lanes would be converted into TOT lanes (except inside I-285, where the current prohibition for through truck trips is maintained), with no need to construct separate TOT lanes.

Measures of the long-term performance of each scenario were developed to determine if any fatal flaws exist in the TOT concept. The study found that under any of the three scenarios:

1. total vehicle hours traveled are reduced with a negligible change in vehicle miles traveled (see Table 48);
2. trucks can save a significant amount of time (see Table 49);
3. congestion in general-purpose lanes is significantly improved (see Table 50); and
4. respectable amounts of revenue can be generated to cover operating and maintenance costs (see Table 51).

Table 48. 2030 Weekday VMT and VHT for TOT Lane Alternatives (PBQD 2005).

TOT ALTERNATIVE SCENARIO	WEEKDAY VMT (K)	CHANGE IN WEEKDAY VMT (K)		WEEKDAY VHT (K)	CHANGE IN WEEKDAY VHT (K)	
HOV-2+ Base	159,787	-	-	6,139	-	-
A1: Major Truck Corridors	160,108	321	0.2%	5,742	-397	-6.5%
A2: Service to Deliveries	160,138	351	0.2%	5,747	-392	-6.5%
A3: Regional TOT Network	159,692	-96	-0.001%	5,843	-296	-4.8%

Table 49. 2030 Trip Times for General Purpose and TOT Lane Alternatives (PBQD 2005).

SAMPLE TRIP AND DESTINATIONS	A1: MAJOR TRUCK CORRIDORS (minutes saved)	A3: REGIONAL TOT NETWORK (minutes saved)
I-75 north to I-285 west to I-75 south		
I-75 at I-285	6	14
I-285 E at I-75 S	32	45
I-75 S at end	51	70
I-75 north to I-285 east to I-85 north		
I-75 at I-285	6	14
I-285 E at I-85 N	27	39
I-85 N at end	68	80

Table 50. 2030 Travel Conditions for General Purpose Lanes (PBQD 2005).

TOT ALTERNATIVE SCENARIO	PERCENT GP LANES OPERATING AT GIVEN CONDITION DURING PEAK HOUR		
	Free Flow	Near Capacity	At Capacity/ Congested
p.m. Peak Hour			
HOV-2+ Base	40	31	29
A1: Major Truck Corridors/ A2: Service to Deliveries	46	32	22
A3: Regional TOT Network	48	28	24
Midday			
HOV-2+ Base	69	28	3
A1: Major Truck Corridors	78	20	2
A2: Service to Deliveries	78	20	2
A3: Regional TOT Network	81	17	2

Table 51. 2030 Regional Revenue Estimates for TOT Lane Alternatives (PBQD 2005).

TOT ALTERNATIVE SCENARIO	WEEKDAY REVENUE (K)				PROJECTED ANNUAL REVENUE (K)
	Light-Duty Truck	Heavy-Duty Truck	Total	Per TOT Lane-mile	
A1: Major Truck Corridors	$186	$142	$327	$694	$89,400
A2: Service to Deliveries	$219	$153	$372	$614	$101,000
A3: Regional TOT Network	$429	$296	$724	$554	$198,000

Multi-state Corridors

With a broader focus on trade, the FHWA (1999) and the Departments of Transportation in Texas, Oklahoma, Kansas, Missouri, Iowa, and Minnesota combined their efforts to conduct a study of I-35 from Laredo, Texas, to Duluth, Minnesota. The purpose of the study was to assess the need for improved local, intrastate, interstate, and international service on I-35 and to clearly define a general feasible improvement plan to address those needs.

A base case and five candidate alternatives were developed based on an assessment of the best features of various scenarios, such as efficiency improvements to the I-35 facility, increased use of railroads, expedited international freight processing, improved commercial vehicle operations, improved intermodal transfers, public transportation strategies, and a do little (base case) strategy.

The preferred alternative, the Trade Focus Strategy (Alternative 4), includes development of a partial North America Free Trade Agreement (NAFTA) Truckway, with larger truck size and weights. For this alternative, the truckway and larger truck size and weights are used only where their implementation could result in lane savings to I-35. This is in the southern portion of the corridor (between Dallas/Fort Worth and Laredo, Texas), where the truck traffic demand projections are the highest. Two truckway options are possible – a separate facility and a truckway within the existing I-35 right-of-way. This strategy assumes the truckway is located within the I-35 right-of-way for environmental and cost purposes. This alternative also includes complete ITS for commercial vehicle operators and pre-clearance centers for U.S., Canadian, and Mexican customs operations.

Based upon a full analysis, the Trade Focus Strategy (Alternative 4) has a number of important advantages over the other alternatives, including providing good overall movement of traffic in the corridor as well as the best economic benefits of the alternatives studied. This option also provided the best reduction in travel times for traffic on I-35, reduction in accident costs and benefit-to-cost relationships, and fewer environmental impacts.

To accommodate truck traffic, the Trade Focus Strategy provides special features for trucks from the Dallas-Ft. Worth area south to Laredo, about 490 miles. Options to consider include provisions for larger truck sizes and weights as well as the option of special lanes for trucks. The location for these lanes can be a separate facility near I-35 or special truck lanes within the I-35 right-of-way. The Trade Focus Strategy includes heavy-duty pavement and bridges throughout the facility.

The Trade Focus Strategy had the best return of all the alternatives as measured by annual costs savings, economic impact, and benefit-cost ratio.

Annual cost savings (in 1996 dollars) during the design year of the project through year 2025, when compared with the base case alternative of "do little" include: $1.15 billion annual vehicle operating cost savings; $1.08 billion annual travel time cost savings; and $151 million annual accident cost savings; a total of almost $2.38 billion annual travel efficiency benefits by 2025.

The economic impact during the construction and operational life of the project, (calculated in 1996 dollars) for the primary impact area is projected to be $20.9 billion in discounted value added; 43,100 permanent jobs created that can be attributed to the I-35 Corridor improvements; more than $30.8 billion in personal income added; and more than $18.4 billion in added wages.

The cost estimate for the Trade Focus Strategy using 1996 cost data is $10.9 billion. This includes costs for roadway, structures, ITS, and engineering and administration.

When the total cost to implement the Trade Focus Strategy is compared to the benefits derived from it, the projection is that $1.86 in benefits will be realized for each dollar expended. The net present value for the strategy is projected to be $5.76 billion, which represents the net economic value of the project to the nation's economy.

Currently under study, a similar multi-state effort is considering I-69, a planned 1,600-mile national highway connecting Mexico, the U.S., and Canada. Eight states are involved in the project. In Texas, I-69 will be developed under the Trans-Texas Corridor master plan.

Exclusive Lane Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation, Tables 52 and 53 summarize relevant findings for exclusive lane performance monitoring and evaluation based on a review of collective guidelines and site-specific evaluations for passenger-focused exclusive lanes and freight-focused exclusive lanes, respectively.

Performance monitoring and evaluation activities for exclusive lanes with a passenger focus closely resemble those activities for HOV lanes, with a focus on increasing person throughput and average vehicle occupancies through increased transit utilization supported by reduced travel times, increased travel time reliability, and enhanced safety. Exclusive lanes with a focus on freight are also interested in reduced travel times, increased reliability, and enhanced safety, but this interest is more commonly motivated by vehicle operating cost savings and with a focus on freight tons rather than persons moved. Uniquely considered for freight-focused exclusive lanes is the pavement deterioration attributable to the redistribution of heavy traffic.

MIXED-FLOW SEPARATION/BYPASS LANES

Collective Guidelines

Collective guidelines for non-arterial mixed-flow separation/bypass lanes were not uncovered. Mixed-flow separation/bypass lanes are typically short in length, providing opportunities for eligible vehicles (typically buses, HOVs, or trucks) to reduce ramp meter delays, bypass spot congestion delays, or avoid potentially unsafe operating maneuvers (Kuhn et al. 2003). The resulting travel time, reliability, and safety benefits attributable to these facilities may be comparably small in magnitude, explaining the lack of focus on performance.

Site-specific Findings - Passenger Focus

Consistently, only a few site-specific studies have been conducted to evaluate the performance of non-arterial mixed-flow separation/bypass lanes, despite their more widespread use. Only California and Oregon reported performance results for non-arterial mixed-flow separation/bypass lane facilities. Other states, including Minnesota and Washington, who use ramp metering bypass for transit and HOVs extensively along the I-35 and I-5 corridors, respectively, have not formally studied performance. (Ramp metering performance has been

Table 52. Exclusive Lane Performance Monitoring and Evaluation Summary-Passenger Focus,

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	bus service levels	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
	Increase throughput	• Daily, hourly volume on exclusive facilities (vehicle, person) • Total, daily, and hourly facility volume (exclusive, GP) • Total, daily, and hourly facility volume (vehicle, person)		P				P	S												M Q A	M Q A	Q A	A	O	O
		• Percent peak-period volume (vehicle, person)		P				P	S												M Q A	M Q A	Q A	A	O	O
		• Per-lane efficiency (speed × pphpl)		P	P		S	P	S												M Q A	M Q A	Q A	A	O	O
		• Vehicle occupancy (per/veh)						P													M Q A	M Q A	Q A	A	O	O
		• Transit ridership • Transit market share	[1] 135%–186% increase (range 5,000–30,000 ppd), at-grade/grade-separated lanes 185% increase (range 435–14,105 ppd), mixed-flow/dedicated lanes	P				P	S			P									M Q A	M Q A	Q A	A	O	O
		• Mode shift	[1] 11%–34% drove car, at-grade/grade-separated lanes 25.1% drove car, mixed-flow/dedicated lanes									P									M Q A	M Q A	Q A	A	O	O
	Increase average travel speeds	• Average lane (exclusive, GP) and facility speed	[1] 17–30 mph, at-grade/grade-separated lanes 12–17 mph, mixed-flow/dedicated lanes		P		S														M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] FTA (2004).

Table 52. Exclusive Lane Performance Monitoring and Evaluation Summary-Passenger Focus (Continued).

GOALS/ OBJECTIVES		PERFORMANCE MEASURES		DATA COLLECTION																	EVALUATION/ MONITORING					
				Continuous Automated			Sampled, Manual			Customer Surveys				Agency Surveys												
		MEASURES	OBSERVED PERFORMANCE/ TARGETS	volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	bus service levels	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION (Cont.)	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility (Cont.)																									
	Decrease average travel times	• Travel time rate (min/mile)			P		S														M Q A	M Q A	Q A	A	O	O
		• Travel time savings (min) • Travel time savings rate (min/mile) • Annual travel-time savings ($)	[1] 26%–55% reduction compared systemwide, at-grade/grade-separated lanes 26%–35% reduction compared with local, mixed-flow/dedicated lanes		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on travel time	[1] 85% report 14 min reduction (average), at-grade/grade-separated lanes 73.2% rate above average or excellent, mixed-flow/dedicated lanes								P										A	A				
	Decrease violators	• Managed lane compliance						S	P											S	M Q A	M Q A	Q A	A	O	O
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)	[1] CV reduced from 18.8%–10.2%, at-grade/grade-separated lanes CV range 0%–10%, mixed-flow/dedicated lanes		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on reliability	[1] 68% perceive improvement, at-grade/grade-separated lanes 65% rate above average or excellent, mixed-flow/dedicated lanes								P										A	A				
	Increase “on-time” performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S														M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] FTA (2004).

Table 52. Exclusive Lane Performance Monitoring and Evaluation Summary-Passenger Focus (Continued).

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	vehicle occupancy	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: bus service levels	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity																	P	S	Q A	Q A		A	O	O
ENVIRONMENT	Decrease overall impacts to the environment and resources																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, PMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S	S													Q A	Q A		A	O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments											P								A	A				
ORGAN. EFFICIENCY	Minimize costs	• Cost for construction (per lane-mile, VMT, PMT)	[1] $5–$7 million/mile, at-grade/grade-separated lanes	P				P	S								P				A O				O	O
ORGAN. EFFICIENCY	Minimize costs	• Vehicle operating costs (per lane-mile, VMT, PMT)	[1] $1 million/year, at-grade/grade-separated lanes	P				P	S							P			S		Q A				O	O
ORGAN. EFFICIENCY	Minimize costs	• Cost-benefit measures		P	P		S									P	P	S	S		A				O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] FTA (2004).

Table 53. Exclusive Lane Performance Monitoring and Evaluation Summary-Freight Focus.

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			Sampled, Manual			Customer Surveys				Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
MOBILITY/CONGESTION	Increase throughput	• Daily, hourly volume on exclusive lanes (vehicle, tons) • Total, daily, and hourly facility volume (exclusive, GP) • Total, daily, and hourly facility volume (vehicle, tons) • Miles of travel (VMT, TMT) • Hours of travel (VMT, TMT)	[3] -0.001%–0.2% change in VMT (range 159,695,000–160,138,000) -4.8 to -6.5 change in VHT (range 5,742,000–5,843,000, simulated 2030)	P	P		S	P		S											M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase average travel speeds	• Average lane (exclusive, GP) and facility speed • Percent of time at capacity/ congested (exclusive, GP)	[3] 29% (base) to 22%–24% decrease at capacity/congested, GP, p.m. peak, simulated 2030		P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease average travel times	• Travel time savings (min) • Travel time savings rate ($/mile) • Annual travel-time savings ($)	[1] 2.5 min/trip (8%), trucks $10 mil annually, trucks $30 mil annually, GP [3] 6 –68 min/trip, major truck corridors 14–80 min/trip, regional TOT network, simulated 2030 [4] $1.08 bil, annually		P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease average travel times	• Customer perceptions on travel time									P										A	A				
MOBILITY/CONGESTION	Decrease violators	• Managed lane compliance							P										S		M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Trowbridge et al. (1996), [2] Taylor (2001), [3] PBQD (2005), [4] FHWA (1999).

Table 53. Exclusive Lane Performance Monitoring and Evaluation Summary-Freight Focus (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
RELIABILITY	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S														M Q A	M Q A	Q A	A	O	O
RELIABILITY		• Customer perceptions on reliability									P										A	A				
RELIABILITY	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S														M Q A	M Q A	Q A	A	O	O
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity • Incident reduction savings ($)	[4] $151 mil, annually															P	S		Q A	Q A		A	O	O
ENVIRONMENT	Decrease overall impacts to the environment and resources																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, TMT)		P	P	S	S							S							Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S														Q A	Q A		A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Trowbridge et al. (1996), [2] Taylor (2001), [3] PBQD (2005), [4] FHWA (1999).

Table 53. Exclusive Lane Performance Monitoring and Evaluation Summary-Freight Focus (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	cargo tonnage	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
SYSTEM PRESERVATION	Maintain or increase overall system service life																									
	Decrease deficient facilities	• Pavement deterioration rate change • Remaining service life		P				P							P						A	A			O	O
		• Roughness index for pavements • Percent of roads with deficient ride quality (VMT, TMT) • Percent of roadway pavement rated good or better		S				S							P						A	A			O	O
		• Maintenance costs per year														P					A	A			O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments											P								A	A				
	Minimize costs	• Cost for construction (per lane-mile, VMT, TMT)	[2] $16.5 bil/38 mi [4] $10.9 bil	S				S									P				A O				O	O
		• Vehicle operating costs (annually, per lane-mile, VMT, TMT)	[4] $1.15 bil, annually	S				S						P							Q A				O	O
		• Cost-benefit measures	[4] 1.86 B/C	P	P		S	P						P		P	P	S	S		A				O	O
	Maximize revenue	• Toll revenue	[3] $89.4 to $198 mil, annually, simulated 2030																	P	M Q A			A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Trowbridge et al. (1996), [2] Taylor (2001), [3] PBQD (2005), [4] FHWA (1999)

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extensively studied; ramp metering bypass by transit and HOVs has not.) Significantly more focus has been directed toward (through the BRT Program in California and North Carolina) mixed-flow separation/bypass lanes on arterial streets, combined with traffic signal priority.

California

Along I-80, use of a bypass lane to provide priority for HOV-3+ and buses approaching the toll plaza on the San Francisco/Oakland Bay Bridge reportedly saves commuters anywhere from 10 to 20 minutes during the morning peak period (Kuhn et al. 2003).

Oregon

A more comprehensive study conducted by Lall and Lucas (2000) investigated the potential for Smart Ramp technology to reduce Portland's U.S. 26 ramp metering delays to transit, school bus, and HOVs. Intended objectives of the Smart Ramp system were to encourage carpooling and the use of public transportation, reduce the impact of ramp meters on the running times and schedule reliability of fixed route and demand responsive buses, and reduce the cost of enforcing ramp meter bypass lane usage restrictions.

Results of a public survey indicated that 23 percent of respondents formed new carpools as a direct result of the Smart Ramp project, 32 percent changed their route because of the Smart Ramp project, and the average carpool contained 2.5 persons. The program appears to save a minimum of 5 to 10 minutes per trip as determined from users' comments.

On a typical day, dwell time for vehicles in the general traffic lane is 257 seconds during the morning period and 129 seconds in the afternoon. Compared with the average dwell time in the bypass lane of 27 seconds, transit, school bus, and HOVs could save between 102 and 230 seconds per trip or 8.50 to 19.17 minutes per week, assuming a 5-day commute week. Assuming a range of incomes, travel-time savings for commuters equates to between \$1.92 and \$16.32 and \$0.85 and \$7.24 per passenger per week.

Tri-Met has the potential to save between \$9.90 and \$22.30 per week per bus as a result of this time savings (i.e., reductions in maintenance, fuel, supervision, tires, and wages). This translates into a yearly savings of \$245,960.

With respect to enforcement, a higher percentage of illegal usage is observed when the ramp is unmonitored (i.e., no physical enforcement presence). Illegal use ranges between 0 to 8 percent and 2 to 25 percent higher during unmonitored morning and evening periods, respectively. When the ramp-meter location is physically monitored using a Tri-Met vehicle, violation rates are high: 36 percent of the vehicles on average were observed using the bypass lane illegally.

Site-specific Findings - Freight Focus

Suggesting common characteristics related to the value of time and, hence, common benefits attributable to ramp metering bypass, Muthuswamy and Levinson (2003) investigated the hypothetical potential for trucks to utilize HOV ramp metering bypass facilities for a fee. Optimal tolls maximizing user benefit, toll authority profit, and system benefit were estimated using queuing analysis. Results showed it is beneficial to open the underutilized HOV lanes to trucks and that to maximize system welfare, trucks should be allowed free use of the bypass. However, free use raises equity issues, so a toll that is politically acceptable, somewhere between the profit-maximizing toll and no toll, should be assessed. More commonly, freight-focused mixed-flow separation/bypass lanes facilities are motivated by a desire to improve operations and safety, with less attention to travel-time savings.

California

Truck bypass lanes were first implemented on I-5 north of Los Angeles in the 1970s along (1) northbound (2.426 miles in length) and southbound (2.452 miles in length) I-5 at the SR-14 split to separate slower moving trucks from general-purpose traffic on the grade and (2) southbound (0.346 miles in length) I-5 at the SR-99 junction near the Grapevine to place truck merges further downstream of automobile merges at I-5 and SR-99. Although these facilities were built for trucks to bypass the interchanges, automobiles and other vehicles also use the lanes to avoid the weaving sections (Kuhn et al. 2003). No reported results were uncovered related to the performance of these facilities.

Oregon

Oregon also provides a truck bypass facility along I-5 near Portland at the Tigard Street interchange, similar to facilities in California. The bypass lane requires trucks to stay in the right lane, exit onto a truck roadway, and reenter traffic downstream of the interchange. Passenger cars may also use this bypass facility. Motivating this facility is the significant grade on the mainlanes of I-5. Commercial vehicles climbing the grade could not adequately maintain speeds, creating operational and safety problems when required to weave across faster moving traffic entering the mainlanes from their right. Following implementation of the truck bypass lanes, truck speeds are typically 50 mph in the merge area, up from 20 to 25 mph previously (Samuel 1999).

Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation, Tables 54 and 55 summarize relevant findings for mixed-flow separation/bypass lane performance monitoring and evaluation based on a limited review of collective guidelines and site-specific evaluations for passenger-focused facilities and freight-focused facilities, respectively.

In brief, performance monitoring and evaluation activities for mixed-flow separation/bypass lanes with a passenger focus very closely resemble those activities for HOV lanes; mixed-flow separation/bypass lanes with a freight focus are interested in improving facility operations and safety, with a secondary interest in reduced travel times and increased reliability.

LANE RESTRICTIONS

Collective Guidelines - Freight Focus

Collective guidelines for evaluation and monitoring of freight-focused lane restriction performance were not uncovered. Similar to prior HOV lane efforts, Gan and Jo (2003) developed operational performance models for truck lane restrictions using VISSIM. Although this study provided proof-positive of VISSIM's ability to successfully reflect truck lane restriction performance, little additional evaluation and monitoring guidance was provided.

Site-specific Findings - Freight Focus

In 1986, FHWA conducted a state survey and reported on truck lane restriction experiences. Common motivations for implementation were to improve highway operations, reduce accidents, preserve the pavement, and improve construction zone operations.

More than half of the states in the U.S. currently employ some type of truck lane restrictions; only Nevada, Florida, Illinois/Wisconsin, Washington, Virginia, and Texas have

Table 54. Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation Summary - Passenger Focus.

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous, Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
	Increase throughput	• Daily, hourly volume on HOV facilities (vehicle, person) • Total, daily, and hourly facility volume (HOV, GP) • Total, daily, and hourly facility volume (vehicle, person)		P				P	S												M Q A	M Q A	Q A	A	O	O
		• Percent peak period volume (vehicle, person)		P				P	S												M Q A	M Q A	Q A	A	O	O
		• Vehicle occupancy (persons/vehicle)						P													M Q A	M Q A	Q A	A	O	O
		• Transit ridership • Carpool use • Transit market share		P				P	S			P									A	A				
		• Mode shift	[2] 23% formed carpools									P									M Q A	M Q A	Q A	A	O	O
	Increase average travel speeds	• Average lane (HOV, GP) and facility speed			P		S														M Q A	M Q A	Q A	A	O	O
	Decrease average travel times	• Travel time savings (min) • Travel time savings ($/mile) • Annual travel-time savings ($)	[1] 10–20 min/trip, a.m. peak [2] 1.7–3.8 min/trip, peak period		P		S														M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on travel time	[2] 5–10 min/trip								P										A	A				
	Decrease delay	• Avg. delay (day and annually) • Avg. delay (veh-, person-, ton-mile)			P		S														M Q A	M Q A	Q A	A	O	O
	Decrease violators	• Managed lane compliance	[2] 55%–64% compliance					S	P										S		M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.
[1] Kuhn et al. (2003), 2 Lall and Lucas (2000).

Table 54. Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation Summary - Passenger Focus (Continued).

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	on-time performance	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
RELIABILITY	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S														M Q A	M Q A	Q A	A	O	O
RELIABILITY	Decrease travel time variation	• Customer perceptions on reliability									P										A	A				
RELIABILITY	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S								S						M Q A	M Q A	Q A	A	O	O
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity																P	S		Q A	Q A		A	O	O
ENVIRONMENT	Decrease overall impacts to the environment and resources																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, PMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S	S													Q A	Q A		A	O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments											P								A	A				
ORGAN. EFFICIENCY	Minimize costs	• Cost for construction (per lane-mile, VMT, PMT)		P				P	S								P				A O				O	O
ORGAN. EFFICIENCY	Minimize costs	• Vehicle operating costs (per lane-mile, VMT, PMT)	[2] $245,960 annual savings	P				P	S							P			S		Q A				O	O
ORGAN. EFFICIENCY	Minimize costs	• Cost-benefit measures		P	P		S									P	P	S	S		A				O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.
[1] Kuhn et al. (2003), [2] Lall and Lucas (2000).

Table 55. Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation Summary - Freight Focus.

GOALS/ OBJECTIVES		PERFORMANCE MEASURES		DATA COLLECTION																	EVALUATION/ MONITORING					
				Continuous Automated			Sampled, Manual			Customer Surveys				Agency Surveys												
		MEASURES	OBSERVED PERFORMANCE/ TARGETS	volumes/classifications	speeds/travel times	density/lane occupancy	travel times	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
MOBILITY/CONGESTION	Increase throughput	• Daily, hourly volume on exclusive lanes (vehicle, tons) • Total, daily, and hourly facility volume (truck, GP) • Total, daily, and hourly facility volume (vehicle, tons) • Miles of travel (VMT, TMT) • Hours of travel (VMT, TMT)		P	P		S	P		S											M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase average travel speeds	• Average lane (truck, GP) and facility speed • Percent of time at capacity/ congested (exclusive, GP)	[1] 20–25 mph increased to 50 mph, trucks, merge area		P	S	S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease average travel times	• Travel time savings (min) • Travel time savings ($/mile) • Annual travel-time savings ($)			P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease average travel times	• Customer perceptions on travel time									P										A	A				
MOBILITY/CONGESTION	Decrease delay	• Average delay (day and annually) • Average delay (veh, per, ton-mile)			P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease violators	• Managed lane compliance							P										S		M Q A	M Q A	Q A	A	O	O
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																									
RELIABILITY	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S														M Q A	M Q A	Q A	A	O	O
RELIABILITY	Decrease travel time variation	• Customer perceptions on reliability										P									A	A				
RELIABILITY	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S														M Q A	M Q A	Q A	A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.

[1] Samuel (1999).

Table 55. Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation Summary - Freight Focus (Continued).

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous, Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity • Incident reduction savings ($)																P	S		Q A	Q A		A	O	O
ENVIRONMENT	Decrease overall impacts to the environment and resources																									
ENVIRONMENT	Decrease fuel consumption	• Fuel consumption (per VMT, TMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRONMENT	Increase air quality/ dec. pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S														Q A	Q A		A	O	O
SYSTEM PRES.	Maintain or increase overall system service life																									
SYSTEM PRES.	Decrease deficient facilities	• Pavement deterioration rate change • Remaining service life		P				P							P						A	A			O	O
SYSTEM PRES.	Decrease deficient facilities	• Roughness index for pavements • Percent of roads with deficient ride quality (VMT, TMT) • Percent of roadway pavement rated good or better		S				S							P						A	A			O	O
SYSTEM PRES.	Decrease deficient facilities	• Maintenance costs per year														P					A	A			O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments											P								A	A				
ORGAN. EFFICIENCY	Minimize Costs	• Cost for construction (per lane-mile, VMT, TMT)		S				S									P				A O				O	O
ORGAN. EFFICIENCY	Minimize Costs	• Vehicle operating costs (annually, per lane-mile, VMT, TMT)		S				S						P							Q A				O	O
ORGAN. EFFICIENCY	Minimize Costs	• Cost-benefit measures		P	P		S	P						P		P	P	S	S		A				O	O
ORGAN. EFFICIENCY	Maximize revenue	• Toll revenue																		P	M Q A			A	O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.
[1] Samuel (1999).

formally studied their effects. Several other states have reported qualitative findings. Arkansas implemented truck lane restrictions to equalize pavement wear. Due to the voluntary nature of the restriction and lack of enforcement, limited redistribution of truck traffic made Arkansas transportation officials deem the restriction unsuccessful. Georgia speculated that less weaving and fewer maneuvers occurred when trucks were restricted to the rightmost lanes. On a rural facility in Wisconsin, low compliance rates, no change in queue length, and decreased speeds in the left lane (trucks were restricted to the left lanes) were reported.

Challenging the comparison of findings over related studies is the variety in motivating factors for the lane restriction, as well as the variety in restriction characteristics (i.e., statewide versus site-specific, number of facility lanes, number of restricted lanes, left or right restricted lanes, peak period versus continuous, etc.). Despite these variations, commonalities across the site-specific studies are described below.

Nevada

In an early study of truck lane restrictions, the Nevada Department of Transportation (NDOT 1983) considered the effects of encouraging trucks (voluntarily) to travel in the left-hand lane to ease the pavement deterioration rate in the well-traveled right lane. For the purpose of this study, vehicles were classified as (1) cars and small trucks, (2) buses, (3) single-unit trucks, and (4) truck combinations. Test sites were determined by the original pavement conditions, environmental effects, and funding availability for routing maintenance improvements. No long-term effects on pavement deterioration rates were studied.

After signs requesting trucks to use left lanes were placed on the highway, 60 percent of the trucks voluntarily traveled in the left-hand lane. This was consistent even 8 months later when a follow-up study was conducted to determine whether the distribution had changed. Distributions of other vehicles (e.g., cars and buses) remained the same. On the basis of the redistribution of trucks on the facility, researchers speculated that recommended improvements could be completed 3 to 5 years early if voluntary lane restrictions were implemented in the entire rural interstate system, resulting in an annual savings in pavement construction of $1.1 million (1998 dollars). Recently constructed projects could achieve an extended life of 5 to 10 years. Furthermore, future construction, reconstruction, and overlays could be reduced by 10 to

20 percent. Although it was beyond the scope of the study, researchers noted that the redistribution of trucks had no significant impact of traffic accidents.

Florida

Along I-95 in Broward County, Florida, a truck lane restriction banning tractor trailers and single-unit trucks from the median lane was implemented. An early study conducted by the Florida Department of Transportation (FDOT 1982) examined the effects on both the operation and safety of I-95 after implementation of the lane restriction. Traffic volume, vehicle classification by lane, speed, and accident data were analyzed. A high compliance rate was discovered when the trucks were redistributed in the non-restricted lanes. The only change in the distribution of passenger vehicles was an increase in the median lane northbound and a decrease of passenger vehicles in the median lane southbound. The speed studies were inconclusive; however, the number of tractor-trailer drivers that violated the 55 mph speed limit increased during the morning peak period and decreased during the afternoon peak period following implementation of the restriction. Safety studies were also inconclusive because of the short analysis period of 2 months.

As a follow-up study to asses the safety effects of truck lane restrictions, Vargas (1992) compared accident data along the restricted I-95 corridor to a control site in Palm Beach County without lane restrictions, from time periods before (3 years) and after (3 years) the implementation of the I-95 lane restriction. Results of the study showed that the Palm Beach site had a significant increase in truck accidents from the before to the after period; the Broward County site did not. In fact, the Broward County site did not exhibit any significant change in accidents following implementation of lane restrictions. In comparison to the Palm Beach site, the truck lane restrictions at the Broward County site effectively reduced the number of truck accidents by 38.43 percent and the number of truck injury accidents by 56.81 percent. For this reason, lane restrictions were recommended as an effective countermeasure to reduce accidents.

Illinois/Wisconsin

Hanscom (1990) investigated the operational effects of truck lane restrictions by observing non-restricted (control) and restricted (test) sections on two, three-lane (per direction) urban-fringe interstates in Chicago and one, two-lane (per direction) rural interstate in Wisconsin.

Considering I-290 near Chicago, with an interest in speed differentials between restricted and non-restricted lanes, investigators manually collected speed data before and after restriction implementation for comparison. It was assumed that speeds would substantially increase in the left lane in the absence of trucks and substantially decrease in the right lanes with the added truck concentration. Speed differentials between the restricted and unrestricted lanes actually decreased after implementation of the truck lane restriction (see Table 56).

Table 56. I-290 Speed Changes Before and After Truck Lane Restriction (Hanscom 1990).

RESTRICTION	AVERAGE SPEED (mph)		SPEED DIFFERENTIAL (mph)
	Left Lane	Right Lanes	
Before Restriction	62.2	59.3	2.9
After Restriction	60.6	58.4	2.2

Hanscom (1990) also considered the change in queue length behind impeding trucks in the non-restricted lanes to reflect added delay potential to non-truck traffic. Average flow delay to vehicles impeded by trucks was recorded at both the restricted and control sites. Although the following-vehicle speed reduction was statistically significant, this reduction did not lead to a significant increase in the queue length behind an impeding truck. A high compliance rate was observed for the three-lane highway sites, where violation rates were as low as 0.9 and 5.7 percent. The violation rate was higher (10.2 percent) for the two-lane site, attributed to the higher concentration of trucks in a single non-restricted lane.

Washington

Mannering et al. (1993) considered the operational, safety, pavement wear, and economic effects of lane restrictions at three sites in Washington's Puget Sound region along I-5 and SR-520, with a fourth site along I-5 serving as a control site. Three types of analyses were performed: (1) an in-depth analysis to determine how the implementation of a lane restriction would impact the operation, safety, and longevity of the facility in addition to how it would economically impact the region; (2) a site comparison analysis to determine whether the results from the in-depth analysis could be applied to other areas in the region; and (3) a survey of truckers, motorists, and industry and enforcement officials regarding lane restrictions. Findings are summarized in Table 57. Based on these findings, truck lanes were not recommended for further implementation in the Puget Sound region.

Table 57. I-5 and SR 520 Performance Before and After Truck Lane Restriction (Mannering et al. 1993).

GOAL AREA	RESULTS
Facility Redistribution	• The proportion of trucks traveling in the left lane prior to the restriction (2.1%) was unchanged following the restriction.
Travel Speeds	• Both trucks and non-trucks experienced a slight but statistically significant increase in average speed.
	• Speeds of vehicle couplets may indicate that trucks are impeding the free flow of traffic; the average speeds for cars following cars and trucks following cars are greater than the speeds of cars following trucks and trucks following trucks.
	• Assuming 100% compliance, the economic loss incurred by a driver who previously had traveled in lane 4 and now had to travel in lane 3 would total $4.84 per year (19.52 minutes of driving time). For the industry as a whole, economic losses would total $1,155 annually (82.2 hours of lost driving time).
Compliance	• Violations increase as congestion increases.
	• Violation rates were 2.1%.
Safety	• Truck-related accidents were proportional in frequency to their per lane volumes.
	• The majority of accidents resulting from merging from an on-ramp, changing lanes to the left, or moving straight was initiated by vehicles other than trucks.
	• The majority of accidents resulting from changing lanes to the right was initiated by trucks.
	• The majority of truck involved accidents resulted only in property damage or minor injuries.
System Preservation	• Even assuming extreme conditions (i.e., 100% restriction compliance and no weather effects on the pavement), a truck lane restriction would have minimal impacts on the life of the pavement.
Customer Satisfaction	• Of the motorists surveyed, 90.85% favored truck lane restrictions, while only 31.96% of the truck drivers favored truck lane restrictions.

Virginia

Truck lane restrictions have been implemented or considered for implementation at a number of sites in Virginia. In 1984, truck lane restrictions were implemented on the Capital Beltway (I-95 and I-495) following a major truck accident. The beltway has four lanes in each direction; the truck lane restriction banned all trucks from the left lane and trucks carrying hazardous materials to the right two lanes. A study was performed to determine the safety effects of the lane restrictions; accident data collected for 2 years prior to and following the lane restrictions were compared (Virginia Department of Transportation 1985).

The results of the study showed that the total accident rate increased 13.8 percent following implementation of the restrictions. Specifically, the number of tractor trailer accidents occurring in the median lane was less than the number of accidents occurring outside the median lane after the tractor trailer had, just prior to the accident, been traveling in the median lane. In other words, the weaving action of trucks moving out of the median lane because of the restriction appeared to result in an increase in tractor trailer accidents. However, since the severity of the accidents did not adversely change (the number of injury crashes decreased approximately 20 percent), it was recommended that the restrictions remain in place. Secondary results of this study reported no observed changes in speed for any vehicle type and no expected change in facility capacity. Motorists supported the program because they felt less intimidated by the trucks.

Results of a subsequent analysis of I-95 conducted in 1988 were consistent with earlier results in that the total accident rate increased when truck lane restrictions were in effect. This repeated observation led to the recommendation that the truck lane restrictions be removed. Despite this recommendation, the truck lane restrictions are still in place (Hoel and Peek 1999).

Considering the potential for truck lane restrictions along the I-64 corridor in Virginia, Garber and Gadiraju (1990) conducted a simulation study to determine speed-flow relationships for different traffic lanes at different locations, to investigate the relationship between congestion and accident rates, to determine the effect of strategies on speed and flow distributions, and to investigate the effects of lane-use restrictions on accident rates and time headways. Investigators collected spot speeds and volume counts from nine locations that had 5 to 40 percent truck traffic. The SIMAN simulation software package simulated a 5-kilometer section of highway. Two types of restrictions were evaluated: one that limited trucks to specific lanes on the highway and one that lowered the speed limit for trucks.

The study showed that restricting trucks to the right lane decreased headways in the right lane at some sites. The study concluded, however, that there were no safety benefits from any of the strategies. Also, there was the potential for increased total accident rates with the implementation of each strategy, particularly with high annual average daily traffic and a high percentage of trucks.

More recently, Hoel and Peek (1999) investigated the potential for truck lane restrictions under various scenarios and for specific case study sites along I-81 in Virginia. A total of 24 scenarios were constructed based on lane restriction status (i.e., restricted or not restricted), degree of uphill grade, and different initial volume distributions by lane. Scenarios were tested on a hypothetical 3-mile section with three lanes in each direction. The volumes ranged from

1,000 to 3,000 vehicles per hour per direction, and truck percentages ranged from 10 percent to 40 percent. Free-flow speed was assumed to be 65 mph.

The case study investigation considered three rural sites with speed limits of 65 mph. The grades of the roadways varied for each site. The percentages of trucks on each site ranged from 21 percent to 35 percent. Three elements were used to evaluate the performance of various exclusive truck lane scenarios: density, lane changes, and speed differential. Each site was simulated with no restrictions, trucks restricted from the left lane, and trucks restricted from the right lane.

Based on the results of both the simulation analysis and the case study analysis, the following general conclusions were reported: restricting trucks from the left lane with steep grades causes an increase in the speed differential; restricting trucks from the left lane with steep grades may decrease density and the number of lane changes; restricting trucks from the right lane causes an increase in the number of lane changes for sites without exit and entry ramps; and site characteristics dictate the effects of truck lane restrictions.

Texas

Extensive studies have been conducted in Texas to examine the operational effects of lane restrictions on rural interstates. Stokes and McCasland (1986), looking at freeways in Houston, San Antonio, and Dallas/Fort Worth, considered the impact of truck lane restrictions as one of six truck regulations that could improve safety and operations on freeways in Texas. Without any quantitative data reported, this study concluded that the restriction of trucks to one lane with mixed traffic does not improve safety and operations, although drivers may perceive this to be the case. However, prohibiting trucks from the left lane where three or more lanes exist would be beneficial, as would restricting trucks to the two rightmost lanes where four or more lanes exist. A short-term recommendation was made to prohibit trucks from the left lane(s) on a trial basis.

Several years later, Zavoina et al. (1990 and 1991) focused on the effects of truck lane restrictions along three six-lane, rural interstate highways with differential speed limits of 65 mph for cars and 60 mph for trucks (vehicles with three or more axles). The three highways included I-20, I-10, and I-35. No control sites were included in this study. The traffic was divided into peak and non-peak periods to account for changes in volume except for along I-10, where no difference existed between peak and non-peak periods. Specific measures of effectiveness for this study included vehicle speeds and vehicle headways or time gaps. This study did not attempt to examine safety impacts or changes in pavement wear.

After the lane restriction was implemented, the distribution of trucks increased significantly to a 62 percent compliance rate. At the I-20 site, the percentage of trucks only increased in the right lane. For the sites along I-10 and I-35, the percentage of trucks increased in both the middle and right lanes. No change was detected in the distribution of cars. While the redistribution of trucks was significant, it appeared to have no measurable impact on the time gaps between vehicles or the speed of cars or trucks. However, the report notes that time gaps for trucks following trucks were less than the time gaps for trucks following cars. It also noted that facility grade significantly affected the speeds of trucks.

In addition to the examination of operational changes, pre-implementation and post-implementation surveys were conducted to determine driver opinion of the effectiveness of lane restrictions and to determine the most effective signing system for both motorists and truck drivers.

The results of the pre-implementation survey showed that 60 percent of the motorists favored truck lane restrictions. Only 28 percent of the truckers favored the restrictions. Truckers thought that the restrictions would cause merging and diverging conflicts, impede cars, and create undue congestion. The second survey, which was administered after the restriction was implemented, showed 48 percent of motorists and 20 percent of truckers favored the restrictions, with a high number of respondents who were unsure whether truck lane restrictions were a good idea.

In 1999, the City of Houston conducted a demonstration project restricting trucks from traveling in the left lane along an 8-mile section of I-10. The results of the demonstration project were generally favorable; compliance rates for the restriction were between 70 and 90 percent. Vehicle crash rates were also reduced during the 36-week monitoring period by a dramatic 68 percent. Several factors, including increased enforcement, may have contributed to that reduction. Traffic studies conducted during the evaluation revealed that there was no significant impact on freeway operations, travel time, frequency of lane changes, or traffic patterns. Public opinion was extremely positive, with 90 percent of automobile users in favor of the restriction (Borchardt et al. 2001).

Most recently, an implementation study was conducted to investigate the feasibility of truck-restricted lanes along I-35 through Austin, Round Rock, and Georgetown, Texas (Venglar et al. 2002). This investigation examined the possibility of restricting trucks from either the leftmost or rightmost travel lane of the I-35 mainlanes in an effort to improve operations and safety within the city limits of Austin, Round Rock, and Georgetown and forms the basis for the current investigation's "before" observations. An evaluation is currently under way to determine the observed performance of the truck lane restriction following implementation.

Lane Restriction Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation, Table 58 summarizes relevant findings for lane restriction performance monitoring and evaluation based on a review of collective guidelines and site-specific evaluations.

Unlike performance monitoring and evaluation activities for freight-focused exclusive or mixed-flow separation/bypass lane facilities, lane restriction performance monitoring and evaluation activities focus on enhancing safety, preserving pavement infrastructure, and improving traffic operations (i.e., reduced travel times and increased reliability) for general-purpose traffic, but often to the detriment of truck traffic.

DUAL FACILITIES

Collective Guidelines

Only a single dual facility – the New Jersey Turnpike – exists in the U.S. As such, the benefit of and consequent need for collective guidelines describing performance monitoring and evaluation activities for this facility type are limited. Not surprisingly, no such documents were uncovered.

Site-specific Findings

New Jersey

The New Jersey Turnpike has a 35-mile segment that consists of interior (passenger car) lanes and exterior (truck, bus, and car) lanes within the same right-of-way. These facilities, referred to as dual-dual segments, were implemented to relieve congestion. For 23 miles, the

Table 58. Lane Restriction Performance Monitoring and Evaluation Summary-Freight Focus.

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			DATA COLLECTION: Sampled, Manual			DATA COLLECTION: Customer Surveys				DATA COLLECTION: Agency Surveys							EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																									
MOBILITY/CONGESTION	Increase throughput	• Daily, hourly volume on exclusive lanes (vehicle, tons) • Total, daily, hourly facility volume (non-, restricted, vehicle, tons) • Miles of travel (VMT, TMT) • Hours of travel (VMT, TMT)		P	P		S	P		S											M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Increase average travel speeds	• Average lane (restricted, non-restricted) and facility speed • Percent of time at capacity/ congested (restricted, non-restricted) • Speed differential (non-, restricted)	[3] 2.9 mph before, 2.2 mph after [5] no change in speed, trucks or other [7] no change in speed, trucks or other		P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease average travel times	• Travel time savings rate (min/mile) • Travel time savings (min) • Annual travel-time savings ($)	[4] 19.52 min/year/truck increase $4.84/year/truck cost 82.2 hrs/year increase for industry $1,155/year cost for industry		P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION		• Customer perceptions on travel time									P										A	A				
MOBILITY/CONGESTION	Decrease delay	• Average delay (day and annually) • Average delay (veh, per, ton-mile)			P		S														M Q A	M Q A	Q A	A	O	O
MOBILITY/CONGESTION	Decrease violators	• Change in lane redistrbution (trucks, other) • Managed lane compliance	[1] 60% of trucks voluntarily traveled in non-restricted lane (no change in other traffic) [3] 94.3%–99.1% compliance, 3-lane facilities 89.8% compliance, 2-lane facilities [4] 97.9% compliance, truck distribution unchanged [7] 62% compliance, no change in other traffic [8] 70%–90% compliance	P					P										S		M Q A	M Q A	Q A	A	O	O
REL.	Increase reliability during recurring and nonrecurring congestion																									
REL.	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S														M Q A	M Q A	Q A	A	O	O
REL.		• Customer perceptions on reliability									P										A	A				

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.
[1] NDOT (1983), [2] Vargas (1992), [3] Hanscom (1990), [4] Mannering et al. (1993), [5] VDOT (1985), [6] Garber and Gadiraju (1990), [7] Zavoina et al. (1990, 1991),[8] Borchardt et al. (2001).

Table 58. Lane Restriction Performance Monitoring and Evaluation Summary-Freight Focus (Continued).

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous, Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	cargo tonnage	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: vehicle productivity	infrastructure condition	operating costs	capital costs	accidents	enforcement levels	toll revenue	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
REL.	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S														M Q A	M Q A	Q A	A	O	O
SAFETY	Increase overall safety levels																									
SAFETY	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity • Incident reduction savings ($)	[2] 34.43% (truck), 56.81% (truck injury) accident decrease [5] 13.8% rate inc., 20% injury acc. decrease [8] 68% rate decrease (w/inc. enforcement)															P	S		Q A	Q A		A	O	O
ENVIRON.	Decrease overall impacts to the environment and resources																									
ENVIRON.	Decrease fuel consumption	• Fuel consumption (per VMT, TMT)		P	P	S	S	S													Q A	Q A		A	O	O
ENVIRON.	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S	S													Q A	Q A		A	O	O
SYS. PRES.	Maintain or increase overall system service life																									
SYS. PRES.	Decrease deficient facilities	• Pavement deterioration rate change • Remaining service life	[1] 5 to 10 year increase	P				P							P						A	A			O	O
SYS. PRES.	Decrease deficient facilities	• Maintenance costs per year														P					A	A			O	O
SYS. PRES.	Decrease deficient facilities	• Construction cost savings	[1] $1.1 mil, annually 10%–20% reduction in future work														P				A	A			O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																									
ORGAN. EFFICIENCY	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments	[4] 90.85% (motorists), 31.96% (trucks) favor [7] 60% (motorists), 28% (trucks) favor before 48% (motorists), 20% (trucks) favor after [8] 90% (motorists) favor										P								A	A				
ORGAN. EFFICIENCY	Minimize Costs	• Cost for construction (per lane-mile, VMT, TMT)		S				S									P				A O				O	O
ORGAN. EFFICIENCY	Minimize Costs	• Vehicle operating costs (annually, per lane-mile, VMT, TMT)		S				S						P							Q A				O	O
ORGAN. EFFICIENCY	Minimize Costs	• Cost-benefit measures		P	P		S	P						P		P	P	S	S		A				O	O

P = primary, S = secondary, M = monthly, Q = quarterly, A = annually.
[1] NDOT (1983), [2] Vargas (1992), [3] Hanscom (1990), [4] Mannering et al. (1993), [5] VDOT (1985), [6] Garber and Gadiraju (1990), [7] Zavoina et al. (1990, 1991), [8] Borchardt et al. (2001).

interior and exterior roadways have three lanes in each direction. On a 10-mile section that opened in November 1990, the exterior roadway has two lanes and the interior roadway has three lanes per direction. Each roadway has 12-foot lanes and shoulders, and the inner and outer roadways are barrier separated. The mix of automobile traffic is approximately 60 percent on the inner roadways and 40 percent on the outer roadways (Samuel 1999).

No formal studies were uncovered that reported the performance of this facility. Hence, with no collective guidance and no site-specific evaluation efforts, recommendations for performance monitoring and evaluation are based solely on comparative facility characteristics of other managed lane strategies that have been more extensively studied.

Dual Facilities Performance Monitoring and Evaluation Summary

Building upon the typical and recommended practices proposed in the various national guidance documents for general freeway performance monitoring and evaluation and relying upon the guidance provided and experiences observed for other comparative managed lane facilities, Table 59 summarizes potential dual facility performance monitoring and evaluation activities. Note that the potential performance monitoring and evaluation activities most closely resemble those of exclusive lane facilities but with a combined passenger and freight focus, since dual facilities are intended to enhance both passenger and freight movement.

Table 59. Dual Facilities Performance Monitoring and Evaluation Summary - Combined Passenger and Freight Focus.

GOALS/ OBJECTIVES		PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated: volumes/classifications	speeds/travel times	density/lane occupancy	Sampled, Manual: travel times	vehicle occupancy	cargo tonnage	violation rates	Customer Surveys: origin-destination	perceived time savings	ridership/mode use	satisfaction	Agency Surveys: vehicle productivity	on-time performance	infrastructure cond.	operating costs	capital costs	accidents	enforcement levels	toll revenue	EVALUATION/ MONITORING: descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility																											
	Increase throughput	• Daily, hourly volume on exclusive facilities (vehicle, person, tons) • Total, daily, hourly facility volume • Total, daily, and hourly facility volume (vehicle, person, tons) • Miles of travel (VMT, PMT, TMT) • Hours of travel (VMT, PMT, TMT)		P	P		S	P	P	S													M Q A	M Q A	Q A	A	O	O
		• Percent peak period volume (vehicle, person, tons)		P				P	P	S													M Q A	M Q A	Q A	A	O	O
		• Per-lane efficiency (speed × pphpl)		P	P		S	P		S													M Q A	M Q A	Q A	A	O	O
		• Vehicle occupancy (per/veh)						P															M Q A	M Q A	Q A	A	O	O
		• Transit ridership • Carpool use • Transit market share		P				P		S			P										M Q A	M Q A	Q A	A	O	O
		• Mode shift											P										M Q A	M Q A	Q A	A	O	O
	Increase average travel speeds	• Average lane and facility speed • Percent of time at capacity/ congested			P		S																M Q A	M Q A	Q A	A	O	O
	Decrease average travel times	• Travel time rate (min/mile)																										
		• Travel time savings (min) • Travel time savings (min/mile) • Annual travel-time savings ($)			P		S																M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on travel time										P											A	A				
	Decrease violators	• Managed lane compliance						S		P											P		M Q A	M Q A	Q A	A	O	O

Table 59. Dual Facilities Performance Monitoring and Evaluation Summary - Combined Passenger and Freight Focus (Continued).

	GOALS/ OBJECTIVES	PERFORMANCE MEASURES: MEASURES	PERFORMANCE MEASURES: OBSERVED PERFORMANCE/ TARGETS	DATA COLLECTION: Continuous Automated			Sampled, Manual				Customer Surveys				Agency Surveys								EVALUATION/ MONITORING					
				volumes/classifications	speeds/travel times	density/lane occupancy	travel times	vehicle occupancy	cargo tonnage	violation rates	origin-destination	perceived time savings	ridership/mode use	satisfaction	vehicle productivity	on-time performance	infrastructure cond.	operating costs	capital costs	accidents	enforcement levels	toll revenue	descriptive statistics	inferential statistics	capacity analysis	simulation	before and after analysis	alternatives analysis
RELIABILITY	Increase reliability during recurring and nonrecurring congestion																											
	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation) (travel time, speed)			P		S																M Q A	M Q A	Q A	A	O	O
		• Customer perceptions on reliability										P											A	A				
	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and trip) • Percent of trips that arrive in acceptable time window			P		S									S							M Q A	M Q A	Q A	A	O	O
SAFETY	Increase overall safety levels																											
	Decrease incident frequency and severity	• Number of incidents (type, location) • Incident severity • Incident reduction savings ($)																		P	S		Q A	Q A		A	O	O
ENVIRON.	Decrease overall impacts to the environment and resources																											
	Decrease fuel consumption	• Fuel consumption (per VMT, PMT, TMT)		P	P	S	S	S	S														Q A	Q A		A	O	O
	Increase air quality/ decrease pollutants	• Tons of pollutants • Days in air quality non-compliance		P	P	S	S	S	S														Q A	Q A		A	O	O
ORGAN. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel																											
	Increase customer satisfaction	• Percentage rated good to excellent • Qualitative customer comments												P									A	A				
	Minimize Costs	• Cost for construction (per lane-mile, VMT, PMT, TMT)																										
		• Vehicle operating costs (annually, per lane-mile, VMT, PMT, TMT)		P				P	P	S									P				A O				O	O
		• Cost-benefit measures		P	P		S	P	P						P		P	P	P	S	S	P	A				O	O

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

A successful performance monitoring and evaluation program – comprising well-defined and quantifiable goals and objectives, related performance measures and targets, manageable supporting data collection and analysis procedures, and a regular and comprehensive reporting plan – supports an agency's provision of day-to-day services, directs facility and administrative management decisions, and guides short- and long-range planning efforts.

Much of the progress made in advancing the state of the practice in performance monitoring and evaluation has considered general freeway facilities. While this information is useful, it lacks specificity for managed lane facilities. Managed lane facilities are unique, typically requiring a higher degree of active (sometimes real-time) management, addressing goals and objectives that are inconsistent with the general freeway facility (i.e., revenue generation, person rather than vehicle throughput, etc.), and accessing an exclusive set of management tools (i.e., gate closures, etc.). These differences may affect how managed lane facility performance is successfully monitored and evaluated.

To address the potential differences between managed lane facilities and general freeway facilities, this investigation was conducted to isolate and document the best performance monitoring and evaluation practices and principles explicitly for managed lane facilities. More specifically, the objectives of this task were to:

- identify positive performance monitoring and evaluation practices for managed lanes (i.e., in published literature or observed practice) that could be recommended for widespread implementation;
- document reportable managed lane benefits that may guide the development of performance "benchmarks" for monitoring and evaluation;
- identify and describe any issues for consideration surrounding performance monitoring and evaluation practices for managed lanes; and
- assimilate this information into recommended guidelines addressing all aspects of managed lane facility performance monitoring and evaluation.

This information forms the basis of the recommendations contained in the *Managed Lanes Manual* developed for TxDOT and FHWA.

The remainder of this chapter summarizes noted guidance for general performance monitoring and evaluation activities and provides typical and recommended practices for performance monitoring and evaluation of managed lane facilities. This chapter concludes by describing next steps to advance the state of the practice for managed lane performance monitoring and evaluation.

GENERAL GUIDELINES FOR PERFORMANCE MONITORING AND EVALUATION

In response largely to TEA-21's requirements for performance monitoring as an eligibility criterion for receipt of federal funding, a number of studies were conducted in the 1990s that focused on guiding or enhancing these activities. These seminal studies culminated in the development of national guidelines for general freeway performance monitoring and evaluation. The *Freeway Management and Operations Handbook* (Neudorff et al. 2003) considers a broader spectrum of topics but devotes one chapter to describing best practices for freeway performance monitoring and evaluation. In addition, the NTOC (2005) recently published results from its *Performance Measurement Initiative* that detail a short list of recommended performance measures that can be used for internal agency management, external communications, and comparative measurement. Most recently and currently under development, *NCHRP 3-68: Guide to Effective Freeway Performance Measurement Interim Report* (NCHRP 2004) provides comprehensive direction for defining and utilizing freeway performance measures and developing a comprehensive freeway performance management program.

This investigation relied heavily upon the guidance provided in these recent documents to ensure consistency with national performance monitoring and evaluation guidelines and to reflect prior lessons learned for these activities. Notable findings and recommendations related to each step of the step-by-step performance monitoring and evaluation process are provided below.

Goals and Objectives

For transportation facilities, including managed lanes, goals and objectives typically focus on mobility and congestion, reliability, accessibility, safety, environmental impacts, system preservation, and/or organizational efficiency. With these various focus areas in mind, successful goals and objectives should:

- be measurable and quantifiable, adequately describing changes in operation;
- consider performance at the system, project, agency, regional, or statewide level and involve the public, local business interests, elected officials, and agency personnel;
- drive the data to be collected, not be driven by data availability;
- consider qualitative (i.e., related to customer satisfaction) goals; and
- prioritize conflicting goals (i.e., system preservation goals may require an increase in maintenance expenditures while agency efficiency goals seek to minimize maintenance costs).

Performance Measures

Similar principles for success exist when defining related performance measures. To be successful, performance measures should be:

- limited in number to prevent data collection and analytical requirements from overwhelming an agency's resources or decision-makers;
- simple and understandable with consistent definitions and interpretations to address the needs of a wide-ranging audience, while still achieving the required precision, accuracy, and detail to facilitate system or program improvement;
- easily captured either automatically using various technologies or manually with minimal manual data entry and processing to produce usable results;
- sensitive to change, able to adequately capture observed changes in system or program performance;
- consistent with staff skills (simplistic evaluation methods with accurate results are preferred over advanced methods that may be erroneous if staff are not adequately trained);
- consistent in time frame with decision-making needs, ranging from real-time to long-term; and
- geographically appropriate with decision-making needs, ranging from corridor-specific to region-wide, statewide, or even nationwide.

Emerging trends or "principles" in the selection of performance measures for transportation facilities are as follows:

- mobility measures should be based on travel time (travel time, or other similar derivatives of speed and delay, is easily understood by practitioners and the public and is applicable to both the user and facility perspectives of performance);
- multiple metrics should be used to report performance;
- traditional HCM-based performance measures (V/C ratio and level of service) should not be ignored but should serve as supplementary, not primary, measures of performance in most cases;
- both vehicle-based and person-based performance measures should be developed (person-based measures provide a "mode-neutral" way of comparing alternatives);
- both mobility and efficiency performance measures should be developed with improvements in efficiency linked to positive changes in mobility;
- customer satisfaction measures should be included;
- three dimensions of freeway congestion should be tracked with mobility measures: source of congestion, temporal aspects, and spatial detail; and
- buffer index – the amount of extra time needed to be "on-time" 95 percent of the time – is emerging as the preferred reliability measure.

Data Collection

Three general categories of data are generally collected to support transportation facility performance monitoring and evaluation: facility use and performance data (i.e., traffic volumes, travel times, and delay); staffing and resource allocation and use data; and event and incident data, including location, duration, and nature. Data can be collected through a variety of means including automatic or manual techniques. Further, data can be collected continuously across a facility or sampled through special studies. Notable lessons learned with respect to data collection are as follows:

- automatic techniques may suffer from reliability problems and questionable accuracy; it is essential to confirm the accuracy of automatically collected data by periodic use of manual devices;
- special studies are typically short in duration and generally focus on collecting data (i.e., vehicle occupancy and transit ridership information) not available through

existing sources; care must be taken to avoid bias when utilizing special studies sampled data;

- to capture motorist perception data, focus groups, stated preference surveys, or revealed preference surveys can be used; each has advantages and disadvantages that should be considered related to the level of information provided and the potential for extrapolation to a larger population; and
- when selecting data collection methods, the cost and accuracy of each method, the availability of local resources to implement each method, the ease of implementation, and the ultimate data analysis requirements should be considered.

Monitoring and Evaluation

Evaluation activities may range from a simplistic analysis of quantitative measures to produce descriptive or inferential statistics to any number of more comprehensive, robust analyses related to capacity and level of service, simulation, before and after effects, or alternatives selection. Capacity analysis and simulation are appropriate for ongoing system monitoring, while before and after and alternatives analysis are more appropriate for evaluation prior to or following implementation.

The required frequency of evaluation (i.e., monitoring) is variable and highly dependent upon the amount of variation observed for a particular facility and constraints upon agency resources. In general:

- continuously collected data (i.e., traffic volumes, travel times, etc.) should be analyzed monthly, quarterly, and/or annually;
- continuously collected data should be compared with supplemental manually collected data (i.e., from travel time studies) at a monthly or quarterly frequency to ensure adequate data quality (higher frequencies of comparisons are required if significant inconsistencies are observed);
- data that have infrequent occurrences (i.e., accidents) should be analyzed annually or every 2 to 3 years;
- similarly, data that require considerable data collection resources (i.e., customer satisfaction surveys) should be analyzed annually or every 2 to 3 years.

In each case, the frequency of evaluation (i.e., monitoring) can decline over time as the facility performance stabilizes.

Reporting

The audience for performance monitoring and evaluation information is broad but can be effectively categorized by jurisdictional levels:

- local, requiring real-time information to select and implement operational plans, provide traveler information, and plan future improvements;
- regional, requiring aggregated real-time information to address the performance of the system and implement and monitor regional response plans;
- state, requiring information specific enough to distinguish modal performance for resource allocation and programming and long-range planning; and
- national, requiring long-term, aggregate information to determine net effect of strategies, support policy making and goal setting, develop/justify legislation, etc.

Common media and formats for relaying performance monitoring and evaluation information include:

- real-time web sites providing specific traveler information (i.e., incidents, etc.);
- operations planning reports supporting daily road or transit operations;
- annual, monthly, and quarterly reports summarizing regional or statewide conditions, recent performance, and trends;
- before and after and issue studies focusing on corridors, times of day, or specific problems (i.e., travel time variations and freight movement);
- project analysis reports, used to support public transportation, operational or demand management programs, or describing total system effects; and
- long-range planning reports providing trend information and travel forecasts, along with more typical planning measures.

GUIDELINES AND PRACTICES FOR MANAGED LANE PERFORMANCE MONITORING AND EVALUATION

Despite the novelty of managed lanes as a traffic management strategy, the diversity of managed lane facility types and the breadth of motivating factors for managed lane implementation, some general consistency in practice was observed with respect to performance monitoring and evaluation. Common goals, objectives, and performance measures were observed across similar facility types. Significant differences were also observed across similar facility types with respect to observed performance outcomes and evaluation methodologies. Differences in observed performance outcomes are likely explained by the variety in facility design (i.e., length of facility, accessibility, etc.) and operation (i.e., eligibility requirements, toll rates, etc.), even within a similar facility type. Differences in the evaluation methodologies used to arrive at these observed performance outcomes likely reflect the available resources for analysis at the time of evaluation and the evolving state of analysis methodologies.

With a focus on the commonalities across similar facility types, Table 60 depicts typical goals, objectives, and performance measures for the various managed lane facilities considered as part of this investigation. More detailed summaries of both commonalities and differences in performance monitoring and evaluation for managed lane facilities were presented earlier in this report (see Tables 21, 37, 52 and 53, 54 and 55, 58 and 59).

Note that in general, passenger-focused managed lane facilities have a primary interest in increasing (person) throughput, reflected as a function of increased average vehicle occupancies and increased travel speeds. Encouraging the mode shift to higher occupancy vehicles is the potential for travel-time savings and travel time reliability. Value-priced and HOT lanes present unique opportunities for toll revenue, capitalizing on the time savings benefit with less emphasis on encouraging mode shift. Safety and environmental effects are of secondary interest, primarily reported to confirm no adverse impacts from implementation of a managed lane facility. Accidents generally occur infrequently and, hence, require a lengthy evaluation period. Environmental effects are loosely estimated as a function of travel speeds.

Freight-focused managed lane facilities, on the other hand, often have a primary interest in safety and a unique interest in preserving the pavement infrastructure. Resulting benefits attributable to time savings are secondary in nature. Hence, freight-focused opportunities for toll revenue (i.e., exclusive lanes and mixed-flow separation/bypass lanes) report limited likely success. Additional observations on a facility-by-facility basis are described below.

Table 60. Common Goals, Objectives, and Performance Measures for Managed Lane Facilities.

GOALS/ OBJECTIVES		PERFORMANCE MEASURES	MANAGED LANE FACILITIES							
			HOV Lanes	Value-priced and HOT Lanes	Exclusive Lanes		Mixed-flow Separation/Bypass Lanes		Lane Restrictions	Dual Facilities
			Passenger	Passenger	Passenger	Freight	Passenger	Freight	Freight	Passenger and Freight
MOBILITY/CONGESTION	Increase overall mobility during recurring and nonrecurring congestion while maintaining accessibility									
	Increase throughput	• Daily and hourly volume on managed lane facilities (vehicle, person volumes) • Total, daily and hourly facility volume (ML, GP, other) • Total, daily and hourly facility volume (vehicle, person, truck volumes) • Vehicle-, person- or truck-hours of travel • Vehicle-, person- or truck-miles of travel	P	P	P	P	P	S	S	P
		• Percent peak period volume (vehicle, person, truck volumes)	S		S		S			S
		• Per lane efficiency (speed × pphpl)	S		S					S
		• Vehicle occupancy (per/veh)	P	S	S		P			S
		• Temporal shift		P						
		• Transit ridership • Carpool use • Transit market share	P		P		P			P
		• Mode shift	S	P	S		S			S
	Increase average travel speeds	• Average lane (ML, GP) and facility speed	P	S	P	P	S	S	S	P
	Decrease average travel times	• Travel time rate (minutes per mile)	S		S					S
		• Travel time savings per mile • Annual travel-time savings ($)	P	S	P	P	P	S	S	P
		• Customer perceptions on travel time	S	S	S	S	S	S	S	S
	Decrease delay	• Average delay (day and annually) • Average delay (vehicle, person and ton-mile)		S			P	S	S	
	Decrease violators	• ML compliance	P	S	S	S	P	S	S	S
REL.	Increase reliability during recurring and nonrecurring congestion									
	Decrease travel time variation	• Std. deviation (travel time, speed) • Variance (coefficient of variation, travel time, speed)	P	S	P	P	P	S	S	P
		• Customer perceptions on reliability	S	S	S	S	S	S	S	S

P = primary, S = secondary.

Table 60. Common Goals, Objectives, and Performance Measures for Managed Lane Facilities (Continued).

GOALS/OBJECTIVES		PERFORMANCE MEASURES	MANAGED LANE FACILITIES							
			HOV Lanes	Value-priced and HOT Lanes	Exclusive Lanes		Mixed-flow Separation/Bypass Lanes		Lane Restrictions	Dual Facilities
			Passenger	Passenger	Passenger	Freight	Passenger	Freight	Freight	Passenger and Freight
REL.	Increase "on-time" performance	• Buffer index (95th percentile travel time by corridor and major trip) • Percent of trips that arrive in acceptable time window	P	S	P	P	P	S	S	P
SAFETY	Increase overall safety levels									
SAFETY	Decrease the frequency and severity of incidents	• Number of incidents (by type and location) • Incident severity • Incident reduction savings ($)	S	S	S	P	S	P	P	P
ENVIRON.	Decrease overall impacts to the environment and resources									
ENVIRON.	Decrease fuel consumption	• Fuel consumption (per PMT, VMT, or TMT)	S	S	S	S	S	S	S	S
ENVIRON.	Increase air quality/ decrease pollutants	• Tons of pollutants • Number of days in air quality non-compliance	S	S	S	S	S	S	S	S
SYSTEM PRESERV.	Maintain or increase overall system service life									
SYSTEM PRESERV.	Decrease deficient facilities	• Pavement deterioration rate change • Remaining service life				P		S	P	P
SYSTEM PRESERV.	Decrease deficient facilities	• Roughness index for pavements • Percent of roads with deficient ride quality (VMT, TMT) • Percent of roadway pavement rated good or better				S		S	S	S
SYSTEM PRESERV.	Decrease deficient facilities	• Maintenance costs per year				P		S	P	P
ORGANIZ. EFFICIENCY	Increase productivity without compromising public's expectations for efficient and effective travel									
ORGANIZ. EFFICIENCY	Increase customer satisfaction ratings	• Percentage of projects rated good to excellent • Qualitative customer comments	S	S	S	S	S	S	S	S
ORGANIZ. EFFICIENCY	Minimize costs	• Cost for construction (per lane-mile, VMT, PMT or TMT)	P	S	P	P	P	P	S	P
ORGANIZ. EFFICIENCY	Minimize costs	• Vehicle operating costs (per lane-mile, VMT, PMT or TMT)	P	S	P	P	P	P	P	P
ORGANIZ. EFFICIENCY	Minimize costs	• Cost-benefit measures	P	P	P	P	P	P	P	P
ORGANIZ. EFFICIENCY	Maximize revenue	• Toll revenue		P		P		P		

P = primary, S = secondary.

High-occupancy Vehicle Lane Performance Monitoring and Evaluation

High-occupancy vehicle lane facilities have the most extensive history of performance monitoring and evaluation; HOV lane facilities experienced early and widespread implementation and, hence, have been the subject of significant study. Early site-specific evaluation studies conducted in Northern Virginia, California, Texas, Washington, Minnesota, and New Jersey were considered by Turnbull et al. (1991), culminating in the *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities*. Building upon this earlier work, Bracewell et al. (1999) supplemented these suggested procedures with more recent site-specific evaluations conducted in Washington and Minnesota to develop a *High-Occupancy Vehicle Monitoring and Evaluation Framework*. This investigation supplemented these guidance documents with additional site-specific evaluations from Massachusetts, New York, Texas, Utah, Georgia, and others. Common observations are described below.

With a primary interest in increasing (person) throughput, HOV lane performance monitoring and evaluation activities commonly consider lane volumes and classifications, vehicle occupancies, carpool use and transit ridership, and increased travel speeds to demonstrate higher performance than general-purpose lane facilities. HOV lane users are attracted by the potential for travel-time savings and travel time reliability and often perceive their travel time saving to be higher than it actually is. HOV lane compliance is of primary concern since illegal use of the lane can discourage its use (and the corresponding shift to higher occupancy vehicles).

Safety and environmental effects are typically of secondary interest, unless the HOV lane was implemented to remedy a particular problem with safety or air quality compliance, as was the case in Massachusetts.

To best compete with more traditional facility expansion projects, HOV lanes typically compare benefits attributable to travel-time savings with the cost of building, operating, and maintaining the facility. In some instances, an observed improvement in safety is also quantified as a primary benefit, although the infrequent nature of accident occurrence and the consequent lengthy required evaluation time often preclude quantification of safety-related benefits.

Table 21, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for HOV lane facilities.

Value-priced and HOT Lane Performance Monitoring and Evaluation

A number of value-priced and HOT lane projects at various sites around the country were initiated through the Congestion Pricing Pilot Program (funded through ISTEA) and, more recently, the Value Pricing Pilot Program (funded through TEA-21). Of most interest to this investigation were projects that are in the operational or demonstration phase, including sites in California, Texas, and Florida. Also considered as part of this investigation, however, were the results of various feasibility studies that considered the potential impacts of value-priced and HOT lanes in California, Minnesota, and Georgia. These efforts, in combination, formed the basis for the following observations.

Value-priced and HOT lane facilities have both similar and distinct motivations from HOV lane facilities. Value-priced and HOT lanes rely on a dynamic (i.e., reflecting real-time traffic conditions) or fixed but varying (i.e., higher flat rate during most congested peak hour) toll rate schedule to encourage:

- mode shift to higher occupancy vehicles (i.e., higher occupancy vehicles travel free or pay a reduced toll rate);
- temporal shift from the most congested peak hour to the shoulders of the peak hour (i.e., when additional excess capacity is available at a reduced toll rate); or
- combined mode and temporal shift (i.e., travelers shift to higher occupancy vehicles to move from the shoulders of the peak hour to the peak hour).

Similar to HOV lanes, value-priced and HOT lanes seek to encourage mode shift to higher occupancy vehicles and promote travel-time savings as a primary facility benefit. Unlike HOV lanes, value-priced and HOT lanes do not exclusively restrict facility use and subsequent travel-time savings on the basis of vehicle occupancy; SOVs or HOVs not meeting standard eligibility requirements can (1) pay a high-rate toll to take advantage of the potential travel-time savings during peak periods and/or (2) alter trip times to take advantage of lesser tolls during the shoulders of the peak periods when additional excess capacity is available (i.e., peak spreading). A significant challenge is separating the performance of the value-priced and HOT lane from standard HOV lane performance.

Table 37, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for value-priced and HOT lane facilities.

Exclusive Lane Performance Monitoring and Evaluation

Exclusive lane facilities can be either passenger-focused (i.e., exclusive busways and dedicated bus lanes) or freight-focused (i.e., exclusive truckways and dedicated truck lanes).

Passenger-focused Exclusive Lanes

Many of the early passenger-focused exclusive lane facilities were converted to HOV lanes, with carpools being the predominant users. Recently, implementation of exclusive busways has resurged under the Federal Transit Administration's BRT Demonstration Program. Summarizing the observed performance of a number of BRT systems currently in the demonstration phase, the *Characteristics of Bus Rapid Transit for Decision-Making Experience with BRT System Performance* (FTA 2004) largely formed the basis of passenger-focused exclusive lane facility performance monitoring and evaluation observations.

Performance monitoring and evaluation activities for exclusive lanes with a passenger focus very closely resemble those activities for HOV lanes, with a focus on increasing person throughput supported by reduced travel times and increased travel time reliability. Transit ridership and transit market share are generally better descriptors of passenger-focused exclusive lane performance than vehicle occupancy or carpool use since exclusive lanes are often limited to only buses. With such limited vehicle use (i.e., buses only), compliance is of secondary concern; violators are easily recognized and cited.

Table 52, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for passenger-focused exclusive lane facilities.

Freight-focused Exclusive Lanes

Supporting information for freight-focused exclusive lane facilities was limited by a lack of facilities either planned or in operation (planned facilities were reported in New York and Massachusetts, but no additional substantive information was uncovered). Hence, observations related to the performance monitoring and evaluation of freight-exclusive lane facilities is largely based on feasibility and simulated impact studies conducted in Washington, California, Florida, Georgia, and along the I-35 multi-state corridor. In addition, feasibility studies are currently under way in Virginia along I-81 and the I-69 multi-state corridor.

Similar to passenger-focused exclusive lane facilities, freight-focused exclusive lanes offer benefits related to reduced travel times and increased travel time reliability, with a focus on cargo throughput rather than person throughput. Because the efficiency of freight movement relates to tangible associated costs, performance outcomes are commonly reported in terms of dollars rather than minutes saved, etc.

Despite the potential for travel time and reliability benefits, freight-focused exclusive lanes are more commonly motivated by potential gains in safety and pavement preservation. Public agency benefits related to the rate of change of pavement deterioration on facilities without any truck traffic and the ability to adequately construct heavy-volume truck facilities are often reported. The potential for truck toll revenue has been considered to support development of new construction facilities; however, the lack of importance placed on travel time reduction or reliability by trucks (likely affected by external factors such as delivery windows, geographic distances, etc.) suggest limited potential.

Table 53, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for freight-focused exclusive lane facilities.

Mixed-flow Separation/Bypass Lane Performance Monitoring and Evaluation

Similar to exclusive lane facilities, mixed-flow separation/bypass lane facilities can be either passenger-focused or freight-focused.

Passenger-focused Mixed-flow Separation/Bypass Lanes

Similar to the facility benefits of HOV lanes and passenger-focused exclusive lanes, passenger-focused mixed-flow separation/bypass lanes seek to increase (person) throughput, reflected as a function of increased average vehicle occupancies and increased travel speeds. Encouraging the mode shift to higher occupancy vehicles is the potential for travel-time savings and travel time reliability. Distinguishing passenger-focused mixed-flow separation bypass lanes from HOV lanes and passenger-focused exclusive lanes is their length. Mixed-flow separation/bypass lanes are typically short in length and are intended to alleviate only site-specific or spot congestion for eligible users (i.e., ramp metering bypass). Given this distinction, travel time related performance of these facilities is more appropriately reported in terms of delay (for interrupted flow) rather than a travel-time savings or travel speed. In addition, compliance is an important factor to consider; the mixed vehicle use (i.e., buses and carpools) and the short duration may tempt violators to use the bypass lane.

Despite common implementation and study of ramp metering performance, ramp metering bypass performance (by transit and HOVs) has not been widely studied. Recent focus (through the BRT Program in California and North Carolina) has been directed toward mixed-flow separation/bypass lanes on arterial streets, combined with traffic signal priority.

Table 54, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for passenger-focused mixed-flow separation/bypass lane facilities.

Freight-focused Mixed-flow Separation/Bypass Lanes

Unlike passenger-focused mixed-flow separation/bypass lanes, freight-focused mixed-flow separation/bypass lanes facilities are more commonly motivated by a desire to improve operations and safety, with less attention to travel-time savings. Representative facilities exist in California and Oregon, but limited examples were uncovered nationally that evaluated the performance of these facilities.

Table 55, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for freight-focused mixed-flow separation/bypass lane facilities.

Lane Restriction Performance Monitoring and Evaluation

More than half of the states in the U.S. currently employ some type of truck lane restrictions; however, only Nevada, Florida, Illinois/Wisconsin, Washington, Virginia, and Texas have formally studied their effects. Several other states have reported qualitative findings. Challenging the comparison of findings over related studies is the variety in motivating factors for the lane restriction, as well as the variety in restriction characteristics (i.e., statewide, versus site-specific, number of facility lanes, number of restricted lanes, left or right restricted lanes, peak period versus continuous, etc.).

Similar to the performance monitoring and evaluation activities for freight-focused exclusive or mixed-flow separation/bypass lane facilities, lane restriction performance monitoring and evaluation activities focus on enhancing safety, preserving pavement infrastructure, and improving traffic operations (i.e., reduced travel times and increased reliability). These enhancements, however, are typically not realized by truck traffic. For example, restricting trucks from the right lane of a facility may extend the remaining life of the pavement structure but may extend truck travel times or decrease safety levels. Similarly, restricting trucks from the left lane may improve travel times for faster moving general purpose traffic but may again extend truck travel times or decrease safety levels.

More so than other managed lane facilities, when monitoring and evaluating freight-focused lane restrictions, it is important to consider impacts to all users of facility and to consider the variety of potential impacts to accurately assess performance. It is also important to assess where and when potential increases or decreases in performance are anticipated and acceptable.

Table 58, presented earlier in this report, provides additional details regarding observed performance, data collection and evaluation, and monitoring methods for freight-focused restricted lane facilities.

Dual Facilities Performance Monitoring and Evaluation

The New Jersey Turnpike – with a 35-mile segment that consists of interior (passenger car) lanes and exterior (truck, bus, car) lanes within the same right-of-way – is the only example uncovered of a dual facility in operation. No formal studies were uncovered that reported the performance of this facility. Hence, with no collective guidance and no site-specific evaluation efforts, recommendations for performance monitoring and evaluation are based solely on comparative facility characteristics of other managed lane strategies that have been more extensively studied.

The potential performance monitoring and evaluation activities for dual facilities most closely resemble those of exclusive lane facilities, with a combined passenger and freight focus, since dual facilities are intended to enhance both passenger and freight movement. Hence, a wider array of measures may be required to adequately describe the performance of dual facilities. Public agencies should prioritize these measures to better manage data collection and analysis resources and avoid conflicting performance goals and objectives.

Table 59, presented earlier in this report, summarizes potential performance measures, data collection and evaluation, and monitoring methods for dual facilities.

NEXT STEPS

The information summarized in this chapter represents an assimilation of information contained in published literature and observed through national practice regarding the monitoring and evaluation of managed lane facility performance. This information represents a significant step in (1) understanding the differences between general freeway facilities and managed lane facilities, (2) supporting local development of a comprehensive managed lane facility performance monitoring and evaluation program, and (3) setting potential performance targets.

While this report represents advancement in each of these areas, information related to ongoing facility monitoring and potential performance targets is still lacking. With respect to managed lane facility performance monitoring, little information is available to support recommendations pertaining to the frequency of monitoring required. In nearly every observed instance, the reported findings resulted from a one-time before and after or feasibility evaluation; few examples were provided regarding changes in these initial observations over time.

With respect to potential performance targets, variation in managed lane facility design and operation and in the measures and methods selected for performance monitoring and evaluation challenged development of a comprehensive list of performance targets for the various facility types. More common performance measures, such as travel-time savings, were well covered but many others were not. As such, agencies are cautioned when considering the observed performance/targets presented here; the reader should carefully consider the facility characteristics before transferring the observed performance results/targets to a comparable local facility. Nonetheless, it was thought useful to include these reported observations to provide a magnitude of scale and direction to the original source for additional information.

As agencies utilize these findings and begin a comprehensive program of performance monitoring and evaluation for managed lane facilities, the level of consistency in performance measures and evaluation methods will improve. In addition, the bank of knowledge related to the required frequency of monitoring and reasonable performance targets for similar facility types will continue to expand.

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