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"Deployment Strategies of Managed Lanes on Arterials"

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METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

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16. Abstract

This report investigates issues related to planning, financing, deployment, and operation of managed lanes on arterials. In this report, a strategy for managed lanes refers to a combination of the managed lane type, the design and implementation, and the scheme for managing traffic on these lanes. Our investigation indicates that high-occupancy vehicle (HOV) lanes, high-occupancy/toll (HOT) lanes, express-toll (ET) lanes, and bus-only lanes are suitable for implementation on arterials in Florida. Details concerning their designs and implementations are discussed along with traffic management schemes such as intersection treatment, segment management, and automatic enforcement. A flow chart for determining an appropriate managed lane strategy for implementation is also provided.

The report also identifies the necessary steps in performance evaluation before and after an implementation of a managed lane project along with other issues such as agency responsibility and use of toll revenue, when applicable. Useful evaluation tools such as sketch, project, and operational planning are also identified in this report. Finally, two procedures are proposed, one for selecting arterials for managed lane implementations and the other for evaluating a deployment plan for managed lanes.

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EXECUTIVE SUMMARY

The objectives of this project are to (a) examine strategies for deploying managed lanes on arterials, (b) identify tools for evaluating their performance, and (c) investigate ways to coordinate the deployment and operations of these lanes on arterials.

- For the first objective, this report reviews the state and national practices for managed lane on arterials in Section 2. Section 3 then identifies the types of managed lanes appropriate for Florida along with related issues such as design, enforcement, and pricing. As a summary, Section 3 also provides a flow chart that can assist in selecting a managed lane strategy for implementation in Florida. Section 4 discusses issues such as the planning, financing, partnerships, and generating public and governmental support for managed lane projects. Required processes such as Congestion Management Process (CMP), the completion of National Environmental Protection Act (NEPA), and a Finding of No Significant Impact (FONSI) are identified.

- For the second objective, Section 2 reviews practical steps for evaluating the performance of managed lanes. Additionally, Section 4 discusses issues in setting operational objectives and policies, both of which influence how managed lanes are evaluated for their performance. Section 5 reviews the literature for tools used in evaluating the effectiveness of managed lanes. These tools are used in sketch, project, and operational planning, and all can be used to analyze managed lane strategies. Typically, key differences among these tools are in modeling resolution, scale, accuracy, data need, and available resources (such as time available of the analysis).

- For the last objective, Section 6 proposes two heuristic procedures, one for selecting arterials for managed lane implementations and the other for evaluating a plan for deploying a set of managed lanes on arterials. Section 6 concludes with case studies of how to deploy managed lanes on a road network in South Florida using fictitious demand data.

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LIST OF ACRONYMS

BRT:	bus-rapid-transit
CMAQ:	Congestion Mitigation and Air Quality Improvement
CMP:	Congestion Management Process
CSS:	Context Sensitive Solutions
DB:	design-build
DBB:	design-bid-build
DBFOM:	design-build-finance-operate-maintain
DOT:	Department of Transportation
EIS:	Environmental Impact Statement
EM:	eligibility-managed
ET:	express-toll
ETC:	electronic-toll-collection
FDOT:	Florida Department of Transportation
FHWA:	Federal Highway Administration
FONSI:	Finding of No Significant Impact
FSUTMS:	Florida Standard Urban Transportation Model Structure
FTA:	Federal Transit Administration
FY:	fiscal year
GARVEE:	Grant Anticipation Revenue Vehicle
GP:	general-purpose
HOT:	high-occupancy/toll
HOT START:	High-Occupancy Toll Strategic Analysis Rating Tool
HOV:	high-occupancy vehicle
ILEV:	inherently low-emission vehicle
IPD:	Innovation Program Delivery
ITS:	Intelligent Transportation Systems
LCV:	longer-combination vehicle
LOS:	level of service
MAP-21:	Moving Ahead for Progress in the 21st Century
modified CRA:	Modified Charles Rivers Associates technique
MOSAIC:	Model of Sustainability and Integrated Corridors
MPO:	metropolitan planning organization
MTP:	Metropolitan Transportation Plan
MUTCD:	Manual of Urban Traffic Control Devices
NEPA:	National Environmental Protection Act
NHS:	National Highway System
O-D:	origin-destination
P3:	public-private partnership
PAB:	private activity bond

PI: pairwise interchange
PM: price-managed
POET-ML: Policy Options Evaluation Tool for Managed Lanes
PTV: Planung Transport Verkehr AG
RFID: radio-frequency identification
ROD: Record of Decision
RTTS: actual travel time saving
SD: steepest decrease
SIB: State Infrastructure Bank
SMArtHOV: Spreadsheet Method for Arterial HOV Facilities
SMITE-ML: Spreadsheet Model for Induced Travel Estimation - Managed Lanes
SOV: single-occupancy vehicle
SPRUCE: Sketch Planning for Road Use Charge Evaluation
STP: Surface Transportation Program
TAP: Transportation Alternatives Program
TEA-21: Transportation Equity Act for the 21st Century
TIFIA: Transportation Infrastructure Finance and Innovation Act
TIP: Transportation Improvement Program
TTI: Texas Transportation Institute
USDOT: United States Department of Transportation
VII: vehicle infrastructure integration
VMT: vehicle miles traveled
VPPP: Value Pricing Pilot Program

1 INTRODUCTION

Over the last 20 years, development trends in Florida continue to focus on areas with existing highway infrastructure. Due to limited right-of-way and operational constraints, Florida Department of Transportation (FDOT) cannot continue to mitigate congestion by widening existing highways alone. It has to also manage traffic on these highways to further reduce congestion and/or improve mobility.

FDOT defines managed lanes as highway facilities or sets of lanes within an existing highway facility where, in responding to changing conditions, operational strategies are proactively implemented using a combination of tools. Managed lanes in this report include high-occupancy vehicle (HOV) lanes, high-occupancy/toll (HOT) lanes, express lanes, bus-only or truck-only lanes, reversible lanes, and contraflow lanes. They have been extensively deployed along freeways and urban expressways in the United States. For example, HOV lanes are preferential lanes designated for exclusive use by vehicles with two or more occupants for all or part of a day (FHWA, 2008a). The deployment of HOV lanes in the United States has evolved over 30 years. A FHWA report (Chang, et al., 2008) identifies 345 HOV facilities in operation or under construction across the nation. As a derivative of HOV lanes, HOT lanes have been attracting attention from governors, transportation officials, state legislatures, and the media. HOT lanes are HOV lanes that allow lower-occupancy vehicles to access them by paying tolls. Currently, there are approximately nine HOT facilities (and three value-priced lanes) in operation around the country, and many others are either under construction or in a planning stage (USGAO, 2012).

In Florida, there are HOV lanes on I-95 in Miami-Dade, Broward, and Palm Beach Counties. These lanes are buffer-separated and activated during peak hours (7AM to 9AM and 4PM to 6PM). When combined, there are 58 HOV lane-miles in each direction (or 116 HOV lane-miles in total), making this HOV facility the longest in the United States. FDOT also implemented HOT lanes, known as 95 Express, on I-95 in the Miami and Fort Lauderdale. When completed, 95 Express will be approximately 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot. It is being constructed in two phases. Phase 1 extends from SR-112/I-195 to the Golden Glades Interchange. The northbound express lanes opened to traffic on July 11, 2008, and tolling began on December 5, 2008. The southbound opened to traffic in late 2009, and tolling began on January 15, 2010. Phase 2, currently under construction, will expand the HOT lanes from the Golden Glades to Broward Boulevard in Broward County. The operating goal of 95 Express is to safely and efficiently maximize the throughput of the facility while ensuring travel speeds greater than or equal to 45 mph on the HOT lanes. To achieve these objectives, dynamic tolling is implemented. During Phase 1, the toll on 95 Express is updated every 15 minutes and varies from \$0.25 to \$7.25.

Similar to above, the majority of managed lanes in the United States have been deployed along freeways. Therefore, the objectives of this project are to (a) examine strategies for deploying managed lanes on arterials; (b) identify tools to evaluate their performance; and (c) investigate ways to coordinate the deployment and operations of managed lanes on both limited-access facilities and arterials.

The remainder of the report is organized as follows:

- Section 2 reviews the literature on managed lanes. In particular, it highlights, e.g., the policies, practices, planning, implementation, design, regulations, and public acceptance of managed lanes on arterials.
- Section 3 gives a definition of a strategy for managed lanes used in this report. The section also identifies the types of managed lanes with potentials for managing traffic along arterials in Florida. The designs, implementation issues, and schemes for managing traffic on these lanes are introduced and discussed. Lastly, a selection and screening process is developed.
- Section 4 identifies steps for performance evaluation before and after the implementation. This section also discusses related topics such as agency responsibility, necessary activities and funding sources for managed lane projects on arterials.
- Section 5 identifies quantitative tools for performance evaluation and provides recommendations for improvements.
- Using case studies, Section 6 explores the impacts that managed lanes have on the surrounding road network and the possibility for coordinated deployment and operations of managed lanes on arterials.

2 REVIEW OF STATE AND NATIONAL PRACTICES FOR MANAGED LANES ON ARTERIALS

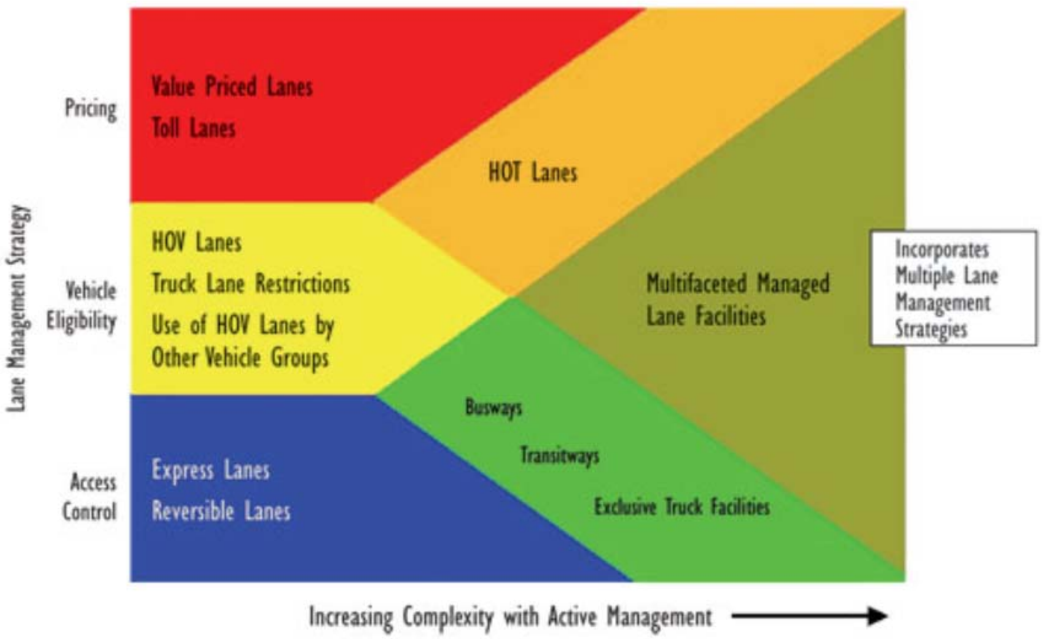
Federal Highway Administration (FHWA, 2008b) defines managed lanes as "highway facilities or a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions." In practice, these lanes are managed using three strategies: pricing, vehicle eligibility, and access control. TABLE 2.1 provides details regarding the characteristics for these strategies.

TABLE 2.1 Strategies and Characteristics of Managed Freeway Lanes

Strategy	Characteristics
Pricing	Pricing refers to the use of tolls to manage travel demand. Tolls may vary with time of day and day of week or by the level of congestion. Higher tolls increase travel costs. Generally, this leads to lower travel demands. Some refer to this form of tolling as congestion or value pricing because less demands mean less cars on freeways or lanes therein. Congestion pricing is different from tolls collected in order to pay for transportation facility constructions. This type of tolls may not be effective in congestion mitigation. However, they do discourage freeway usage, especially when there is a free alternative.
Vehicle Eligibility	The lanes are managed by allowing certain vehicles or restricting others. Requiring vehicles that satisfy a minimum occupancy in HOV lanes is an example of an eligibility restriction.
Access Control[1]	The lanes are managed by controlling access using lane separation and designated access points.

Below, FIGURE 2.1 graphically illustrates all potential types of managed lanes, some of which involve multiple strategies. On the left of the diagram (or along the vertical axis), the figure lists three principal management strategies. Along the horizontal axis, moving from left to right involves combinations of strategies and typically indicates higher level of complexity in terms of management and/or enforcements. Inside the rectangular region formed by the two axes, polygons with different colors indicate types of managed lanes. (Many of these are described and discussed in subsequent sections.) Those further away from the vertical axis toward the right-hand-side involve policies and enforcements that are more complex and may require advance technology.

1 Ramp metering is another form of access control. In practice, ramp meters are installed on entrance ramps for highways and they do not control access to individual lanes.



Source: FHWA (2008b)

FIGURE 2.1 Types of Managed Lanes

For example, value-priced and toll lanes use tolls to managed usage demand in order to, e.g., mitigate congestion and ensure an acceptable of level of service. They are at the top in a red polygon and bordered by the vertical axis because they use pricing and are relatively simple to implement and managed. To the right of value-priced and toll lanes are HOT Lanes. These managed lanes are a combination of toll and HOV lanes and the polygon for HOT lanes is orange, a mixture of red and yellow. Compared to value-priced and toll lanes, HOT lanes require a more complex operational policy to manage and its enforcement requires determining numbers of occupants in vehicles, a rather difficult task to perform accurately in practice. The multifaceted facilities on the far right of the diagram are those that incorporate or blend together multiple lane management strategies.

In the above FHWA's definition, managed lanes are lanes or facilities on highways or freeways. Some consider them as a "freeway-within-a-freeway" because managed lanes are usually freeway lanes that are separated from general-purpose (GP) lanes (FHWA, 2008b). While the concept of managed lanes is in principle applicable to arterial roadways or, more simply, arterials, it is not clear that every type and/or strategy in FIGURE 2.1 can be effectively implemented on arterials because traffic conditions on them are different. Freeways generally serve long distance trips and have speed limits between 55 and 70 mph. They also have a limited number of access points to maintain high speed limits and traffic volume. Unless they are entering or exiting, vehicles on freeways generally travel at similar speeds.

Designed to deliver traffic from collector roads to freeways or expressways and between urban centers, typical arterials have many intersections, most of which allow left turns and some permit U turns. Vehicles from local streets access arterials via these intersections. Some vehicles also enter arterials via abutting driveways that provide access to business and other land-use activities. Thus, it may be difficult politically or otherwise to restrict access to arterials to, e.g., a limited number of intersections without creating hardships and/or inconveniences to certain groups and/or organizations. While vehicles on freeways generally travel at similar speed, buses, private cars, and commercial vehicles, for example, stops along arterials to load and unload passengers, access local business, and make deliveries, respectively. Curb lanes on arterials may be reserved for bicycles, parking, delivery, and/or bus stops. These factors make it difficult to promote safety, maintain speeds, and improve travel-time reliability on arterials. Therefore, it is not clear that every arterial can be managed to achieve some of the objectives, goals, and/or characteristics of managed freeway lanes, particularly when tolls are charged.

Below, the next two sections highlight policies, practices, planning, implementation, design, regulations, public acceptance, environmental considerations, traffic conditions, and facility performance of both managed facilities on freeways and arterials.

2.1 Managed Freeway Lanes

The literature on managed freeway lanes, particularly those focusing on HOV and HOT lanes, is vast. Over the years, several publications (e.g., FHWA, 2004 and 2008b, Perez et al., 2012, and Kuhn et al., 2002) review and/or summarize findings and experiences with managed freeway lanes across the United States. Often, these publications also give guidance when choosing a method for implementing these lanes. Our objective is not to repeat the content of these publications here. Instead, we summarize the findings and lessons learned from managed freeway lanes on aspects specified in the task order and those relevant to arterials. The latter is the topic for Section 2.2.

We group managed freeway lanes into two main categories: those managed by vehicle eligibility and others by price and eligibility. For simplicity, we refer to these two categories as eligibility-managed (EM) and price-managed (PM) freeway lanes, respectively. Note that the name of the second category may seem inaccurate. However, allowing HOVs to travel on HOT lanes for free is akin to charging them zero toll. Thus, managing freeway lanes by price and vehicle eligibility can be viewed as managing by price alone. Among the two categories, PM freeway lanes are more flexible and include EM freeway lanes as special cases where the toll prices are zero for eligible vehicles and extremely high for those ineligible. Nationally, there is a trend toward PM freeway lanes.

Eligibility-managed Freeway Lanes: There are two main types of freeway lanes managed by eligibility: bus-only and HOV. The former allows only buses and the latter permits HOVs as well as others such as motorcycles and hybrid vehicles in most cases during peak travel periods. Bus-only lanes on freeways are typically part of a bus-rapid-transit (BRT) system. When (transit) buses are considered as vehicles with a (perhaps, extremely) high occupancy, bus-only and HOV lanes are in principle the same. The main difference is in the occupancy requirement. On HOV lanes (see FIGURE 2.2), the occupancy is, at minimum, either 2 or 3 persons. On the other hand, the minimum occupancy[2] for bus-only lanes may be 45.

Historically, HOV lanes were originally bus-only lanes in several congested expressways in northern New Jersey, Washington, D.C., and Los Angeles during 1960s. When a bus strike occurred in 1976, Los Angeles temporarily allowed carpools to use the El Monte Busway[3] along

2 The term "occupancy" is used loosely here because buses with no passenger can still use bus-only and bus-toll lanes for free. On the other hand, vehicles with no passenger (i.e., solo drivers) cannot use HOV lanes.
3 The El Monte Busway is now part of HOT lanes under the Metro Express Lanes project in Los Angeles.

I-10. Since then, routes employing HOV lanes grew from 125 route-miles in 1985 to over 1500 route-miles by 2005.

FIGURE 2.2 Example of HOV Lanes from California

<u>Price-managed freeway lanes</u>: There are four main types of freeway lanes that are managed by both pricing and eligibility. They include bus-toll, HOT, express-toll (ET), and truck-only toll lanes.

- <u>Bus-toll and HOT Lanes</u>: Similar to bus-only lanes, bus-toll lanes are typically part of a BRT system. Buses can freely travel on BT lanes and other type of vehicles may access them for a fee. Fees may vary with classes of vehicles, time and/or traffic conditions. Similar to bus-only and HOV lanes, bus-toll and HOT lanes are the same in principle. In most cases, HOVs can freely use HOT lanes (see FIGURE 2.3). Single-occupancy vehicles (SOVs) or lower occupancy vehicles have to pay tolls to use them. When buses are considered as a type of HOVs, bus-toll and HOT lanes are essentially the same. As before, the key difference between bus-toll and HOT lanes is in the occupancy requirement. Bus-toll lanes require a higher occupancy[4] than HOT lanes.

  HOT lanes were introduced in the mid-1990s to better manage HOV lanes by regulating demand more finely via pricing and vehicle eligibility. Electronic toll collections allow HOT lanes to be implemented without tollbooths. This makes HOT lanes attractive to both motorists and transportation agencies. San Diego was the first to implement HOT lanes

[4] See the previous footnote regarding our use of the term "occupancy" for buses.

on I-15 between the Orange and Riverside County in California. The same can be said about convert bus-only to bus-toll lanes. Recently, the Tampa Hillsborough Expressway Authority is studying new bus-toll lanes (see, Stone, 2013).

FIGURE 2.3 A Sign Showing Toll Rates above I-394 HOT Lanes in Minneapolis[5]

- ET Lanes: These lanes consist of individual roadways or lanes therein that motorists can use by paying tolls. Tolls may vary with classes of vehicles, time and/or traffic conditions. In principle, ET lanes charge all vehicles including HOVs and do not provide the same level of incentives for ride-sharing like HOT lanes.

The distinction between HOT and ET lanes in practice is unclear because many have incorporated the terms "express" or "express-lanes" into the names of their HOT lane projects (Perez et al., 2012). Currently, there is only one true ET lane operating in the United States. Maryland Transportation Authority opened its I-95 Express Toll Lanes (see FIGURE 2.4) for traffic toward the end of 2014. All vehicles using these lanes must pay tolls that vary from $0.70 for 2-axle and motorcycles between 9PM and 5AM using E-ZPass to $19.74 for vehicles with 6-axle and more during peak hours via Video Tolling. For the latter, the registered owner of the traveling vehicle is mailed a Notice of Toll Due or NOTD.

[5] Source: http://www.mnpass.org/

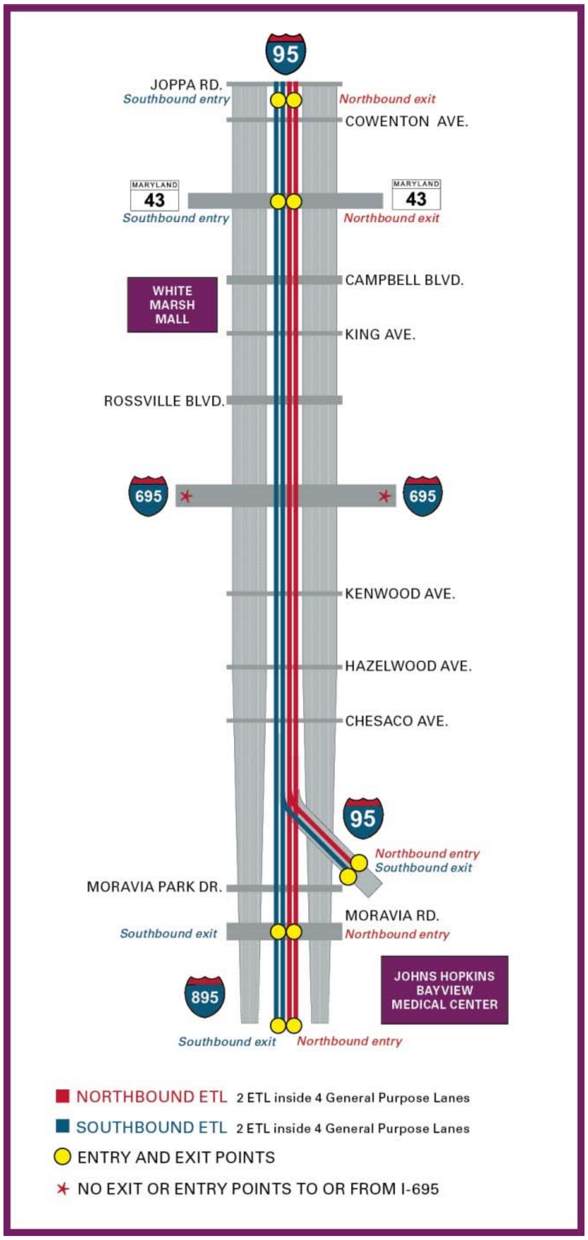


FIGURE 2.4 Maryland Transportation Authority's I-95 Express Toll Lanes

- Truck-only and Truck-only Toll Lanes: These lanes are dedicated to the exclusive use of trucks. Other classes of vehicles are not allowed on these lanes. Trucks must pay tolls to use truck-only toll lanes.

Currently there are very few truck-only facilities in the United States and none of them require tolls (Cambridge Systematics, 2009). Instead, most states restrict trucks to use certain lanes (e.g., the two right most lanes), but all vehicles can also use them. Although there have been several studies and proposals, there is currently no truck-only toll lane in the United States because of several operational and institutional issues (Charlotte Region, 2007). One of which is the need to provide two directional lanes so that trucks can pass one another in order to maintain service capacity and operational benefits. According to Turnbull (2002), studies and plans for truck-only toll in Los Angeles (I-710 and SR 60 corridors), Atlanta (I-75 and I-285 corridors) and Virginia (I-64 and I-81 corridors) did not moved forward to the construction phase.

2.1.1 Policies

In general, policies developed for specific freeway facilities or agencies should address land use, economic development, congestion levels, environmental factors, impacts on mixed flow lanes, safety, cost, and support services and facilities (TTI et al., 1998). Below are policies or goals that address the management of freeway lanes presented above.

Eligibility-managed freeway lanes: Basically, the policy or goal of these lanes is to move more people in fewer vehicles. By using the dedicated lanes, buses and HOVs are able to bypass congested traffic, save time, and realize more predictable (or reliable) travel times. Ideally, these benefits should provide sufficient incentives for transit services, carpools, or vanpools.

Although different, all published goals for EM freeway lanes always encompass the above basic goal. For example, the HOV Systems Manual (Turnbull and Capelle, 1998) states that "HOV facilities are intended to help maximize the person carrying capacity of the roadway… by altering the design and/or operation of the facility in order to provide priority treatment for high-occupancy vehicles." Other regional agencies have more expanded goals and objectives and several are listed TABLE 2.2.

TABLE 2.2 Policies of Eligibility-Managed Freeway Lanes

Agency	Goals
State of California	• Increase people-moving capacity • Reduce congestion • Provide travel time and cost savings • Increase system efficiency • Improve air quality
Minneapolis, Minnesota	• Maximize people-moving capacity • Provide support for bus services and rideshare programs
State of Texas	• Increase people per vehicle • Preserve person-movement capacity • Enhance bus operations
State of Washington	• Maximize people-moving capacity • Mitigate transportation related pollution • Reduce fuel consumption
Washington, D.C.	• Increase people per vehicle • Preserve person-movement capacity • Enhance bus transit operations • Support air quality improvements • Provide predictable travel times

<u>Priced-managed freeway lanes</u>: The policies or goals of these lanes include (Perez et al. 2012):

- Traffic Management: Optimal use of freeway capacity, reduce congestion, and a better management of traffic volume and condition.
- Revenue Generation: Generate revenue to pay for the cost of implementing and operating the lanes and to support other transportation needs.
- New Travel Options: Provide new options to motorists (particularly solo drivers) in congested freeways.
- Enhance Transit Service: Provide faster transit service and improve travel-time reliability.

2.1.2 Practices

The most common reason for considering managed freeway lanes is to release recurring congestion. Freeway congestion occurs when average speeds fall below 35 mph for a prolonged interval (two to three hours) during peak travel periods (Perez et al., 2012). TABLE 2.3 lists conditions when EM and PM freeway lanes can be effective.

TABLE 2.3 Conditions for Managed Freeway lanes

Conditions	Eligibility-Managed	Price-Managed
Lack of free-flowing parallel routes: Managed freeway lanes work best in metropolitan areas with high-density corridors where there are limited travel options.	Effective	Effective
Lack of planned future improvements: The corridor or region does not have enough future capacity planned to meet current and future demands when considering all transportation modes and traffic patterns.	Effective	Effective
Congested HOV lanes: Priced-managed freeway lanes can be effective when the demand for an HOV lane exceeds the capacity of a single lane, but cannot justify the addition of a second HOV lane.	Not applicable	Effective
Under-utilized HOV lanes: Priced-managed freeway lanes can be effective when the demand for an HOV lane is below its operational capacity and there is congestion on the parallel GP lanes.	Not applicable	Effective
Sufficient HOV demand: There is sufficient demand among transit and rideshare users to justify a dedicated lane.	Effective	Not applicable

Among the above conditions, the lack of free-flowing parallel routes suggests that adding new managed capacities to an existing freeway network can mitigate congestion. On the other hand, conversion to PM freeway lanes may be more effective at managing traffic on congested or under-utilized HOV lanes.

The tables below provide examples of the managed freeway lanes in the United States.

TABLE 2.4 Managed Freeway Lanes in the United States

Region	Name	Corridor	Opened[a]	Miles	Lanes	Reversible	Barrier with Untolled Lanes
Orange County	91 Express Lanes	SR-91	Dec 1995	10	4	No	Plastic Posts
San Diego	I-15 Express Lanes	I-15	Dec 1996	20	4	Partial	Concrete Wall
Houston	Katy Freeway Managed Lanes	I-10	Jan 1998	12	4	No	Plastic Posts
Houston	Northwest Highway QuickRide	US-290	Dec 2000	15	1	Yes	Concrete Wall
Minneapolis	I-394 MnPASS Express Lanes[b]	I-394	May 2005	8	2	Partial	Painted Lines / Concrete Wall
Salt Lake City	I-15 Express Lanes	I-15	Sept 2006	40	2	No	Painted Lines
Denver	I-25 Express Lanes	I-25	June 2006	7	2	Yes	Concrete Wall
Seattle	SR-167 HOT Lanes [c]	SR-167	May 2008	12	2	No	Painted Lines
Miami	95 Express	I-95	Dec 2008	7	4	No	Plastic Posts
Minneapolis	I-35W MnPASS Express Lanes [c]	I-35W	Sept 2009	16	2	No	Painted Line
Bay Area	I-680 Sunol Express Lanes[d]	I-680	Sept 2010	14	1	No	Painted Lines
Atlanta	I-85 Express Lanes	I-85	Sept 2011	16	2	No	Painted Lines

[a] This date refers to the first opening of the HOT lane while the remaining columns refer to current conditions. In some cases, particularly San Diego (I-15) and Houston (I-10), the facilities have been expanded so that current conditions do not reflect those when the lane opened.
[b] Minneapolis (I-394)is composed of two segments. The western segment from I-494 to SH-100 consists of a single dedicated lane in each direction painted line separated from the general purpose lanes. The eastern segment from SH-100 to I-94 consists of two reversible lanes concrete barrier separated from the general purpose lanes.
[c] HOT lane is longer in the northbound direction than the southbound direction. The longer length is presented here and used for subsequent calculations.
[d] This lane currently only operates in the southbound direction. Subsequent calculations, such as bus ridership, consider flows only in one direction.

Source: Perez et al. (2012)

TABLE 2.5 Characteristics of Managed Freeway Lanes in the United States

Region	Corridor	Tolling				HOV		Notes
		Approach	Max (¢/mile)	Days	Hours	#	Tag	
Orange County	SR-91	Scheduled	98	Everyday	24	3+	Yes	HOV3 pays ½ price of toll in eastbound lanes from 4:00 – 6:00pm weekdays, otherwise HOV3 is free
San Diego	I-15	Dynamic	40	Everyday	24	2+	No	--
Houston	I-10	Scheduled	33	Everyday	24	2+	No	HOV2 only free 5:00 – 11:00am and 2:00 – 8:00pm on weekdays. Otherwise HOV2 is tolled.
Houston	US-290	Scheduled	13	Weekdays	1¼	3+	No	During tolling hours (6:45 – 8:00am), HOV2 can buy access to this HOT3 lane. At other times, this lane operates as a HOV2 lane.
Minneapolis	I-394	Dynamic	100	Everyday[a]	22	2+	No	The reversible lanes are HOT2 at all times except when they close for the two direction changes on weekdays, each of which takes an hour. The dedicated lanes are HOT2 during peak hours in the peak direction (6:00 – 10:00am eastbound; 2:00 – 7:00pm westbound).
Salt Lake City	I-15	Dynamic	10	Everyday	24	2+	No	--
Denver	I-25	Scheduled	57	Everyday	20	2+	No	HOT2 at all times except when they close for the two direction changes on weekdays, each of which takes two hours.
Seattle	SR-167	Dynamic	75	Everyday	14	2+	No	Tolling hours are from 5:00am – 7:00pm everyday.
Miami	I-95	Dynamic	100	Everyday	24	3+	Yes	HOV3 is restricted to three or more pre-registered adults commuting to work. No 'informal' HOV.
Minneapolis	I-35W	Dynamic	50	Weekdays	9	2+	No	HOV2 always free. HOT2 during peak hours in the peak direction (6:00 – 10:00am northbound; 2:00 – 7:00pm southbound).
Bay Area	I-680	Dynamic	54	Weekdays	15	2+	No	Tolling hours are from 5:00am – 8:00pm weekdays.
Atlanta	I-85	Dynamic	90	Everyday	24	3+	Yes	HOV3 status must be set for transponder in advance.

[a] Minneapolis (I-394) tolls everyday on its reversible portion and on weekdays on its dedicated lanes. It is here classified among the facilities that toll everyday.

Source: Perez et al. (2012)

2.1.3 Planning and Implementation

Below are the steps for planning and implementing managed freeway lanes from Perez et al. (2012). They are similar to those associated with any highway improvement and align with the metropolitan planning organization (MPO) and National Environmental Protection Act (NEPA) processes.

- **Pre-planning**: Once the need for an improvement is identified, the responsible transportation agency—often in coordination with the local MPO—identifies and reviews conceptual, operational and physical solutions for their effectiveness, anticipated cost, ease of implementation, and acceptability to the public. The decision to proceed with the improvement project should be weighed against other needs facing the state and local region.

- **Planning**: If the project sponsor makes a decision to proceed with the project, the project should be incorporated into the MPO's long-range Metropolitan Transportation Plan (MTP) that identifies transportation needs and policies over a 20-year horizon. Once in the MTP, federal funding may be used to support planning work and the completion of NEPA environmental clearance documents. During this process, the project sponsor should narrow and refine the project as well as develop alternatives.

  The process culminates with the identification of a preferred alternative that must be approved through a Categorical Exclusion, a Finding of No Significant Impact (FONSI) upon the completion of an Environmental Assessment, or a Record of Decision (ROD) upon completion of an Environmental Impact Statement (EIS). Projects must also be incorporated into the MPO's Transportation Improvement Program (TIP), a fiscally constrained plan identifying the projects in the MTP to be completed in the coming four-year cycle.

- **Design and Procurement**: Once the MPO and NEPA requirements and funding commitments have been completed and secured, the project sponsor completes design work for the preferred alternative and then puts the project out to bid.

  If the project is being procured via the traditional design-bid-build (DBB) model, the project sponsor would retain a design consultant to complete the final design drawings and hold a second procurement for project construction. The qualified contractor that submits the lowest bid is awarded the project. Alternatively, if the project sponsor chooses to procure the project on a design-build (DB) or design-build-finance-operate-maintain (DBFOM) concession basis, a design-builder or private concessionaire normally completes the final design work. The sponsor must also perform additional analyses to determine if DBFOM procurement is feasible. These would include conducting a financial feasibility analysis to determine the "base financial case" or the cost if the project sponsor builds, operates, and maintains the project. If offers submitted by private developers are better than the base financial case, then the ones with the lowest cost deliver a better value and one of them should be accepted. For PM freeway lane projects, the sponsor should also consider whether the project can be funded from forecasted toll proceeds.

- **Construction**: During the construction phase, a private contractor, design-builder, or private development partner builds the project according to the design or design specifications and implementation schedule established in the construction contract. The project sponsor supervises the construction to ensure that the completed project is consistent with the design and meets the necessary quality standards.

- **Operation and Maintenance**: Once completed to the satisfaction of the project sponsor, the new facility begins its operation. With traditional DBB or DB procurements, the project sponsor assumes responsibility for maintaining and operating the managed freeway lane. With DBFOM concessions, the private developer operates and maintains the facility for a designated concession period. During this period and depending on the project, the private developer has the right to collect toll revenues or receive availability payments from the project sponsor. In some cases, the project sponsor or other public toll agency might be responsible for toll collection. Responsibility for enforcement and incident management remains with the appropriate public agencies.

Below are comments on how to plan for managed freeway lanes from the literature:

- In Ungemah and Swisher (2006), the authors address the following issues within the conceptual development of the HOT lane conversion process from the perspective of the implementing agency's project manager.

  - Understanding the potential excess capacity is important for evaluating the general feasibility of HOT lanes in the conceptual development portion of the HOV to HOT conversion process.
  - Significant and recurring congestion in the adjacent GP lanes is required for successful HOT-lane implementations.
  - From the project manager's perspective, non-barrier-separated HOT lanes have to address the complicated issues related to weaving, safety, enforcement, toll zones, and toll rates.
  - Because the funding for the HOV lanes were mainly from FHWA or Federal Transit Administration (FTA) grants, project managers need to demonstrate in the proposal that the proposed HOT lane can maintain travel times throughout the day and especially during peak periods.
  - The primary objective of the HOT lane program should be identified and extended throughout the lifetime of the program.
  - Instead of revenue maximization, congestion relief or mobility enhancement should be the primary factor in the project's traffic-and-revenue studies.
  - The implementing agency should consider (a) how to integrate HOT lane conversion project into an existing toll system, and (b) how the project accommodates the broader goals and objectives of a statewide or region-wide system.
  - To progress positively in public opinion, project managers and partners for HOT lanes should make concerted efforts and use mechanisms appropriate to their regions.
  - Project manager should build political support for the HOT-lane conversion process by providing relevant information to policy makers.

- In Munnich and Buckeye (2007), the authors discuss the issues concerning the I-394 MnPASS express lanes in Minnesota.

  - Double solid white-lines was not causing excessive weaving and enforcement problems, but instead worked well and might have actually improved safety for buses and other motorists.
  - Although the revenue continues to rise, the concern about how excess revenues above operating and capital costs did not exist at the end of the first year of operation because revenue only covered operating costs.
  - MnPASS transponders have been leased more than expected, but the utilization by individual customer is less than expected.
  - Customers could grasp and understand the signs with dynamic and multiple prices quickly.
  - The enforcement with the double solid white-lines is working well with drivers complying with the lines and reduced violation rates from the previous HOV-lane levels.
  - Accident rates have dropped slightly since the introduction of MnPASS.
  - There have been no negative impacts on transit or carpoolers due to the adaptation of the HOV lanes to HOT lanes and there may be some safety benefits for buses.
  - Because congestion has been reduced in the entire corridor, MnPASS users and users of the GP lanes both benefit and people of all income levels use and support the project.
  - The I-394 MnPASS project also offers a number of lessons for transportation practitioners such as assembling a knowledgeable and multidisciplinary team, engaging the community in the planning process, tapping outside experts and experience, being prepared to respond quickly to problems and make corrections, and learning and sharing knowledge with others.

- In Loudon et al. (2010), the authors conduct a survey of agencies that had been directly involved in congestion pricing and managed lane project in 10 metropolitan areas in the United States and report the following:

  - Reducing congestion should be at least as important as revenue generation when evaluating congestion pricing and managed lanes options.
  - Managed lane projects should be incorporated into metropolitan planning process and gain stakeholders' support and public acceptance. Private sector could also be involved as a partner.
  - Continued support for the assessment of congestion pricing and managed lanes projects is important for continued consideration and implementation of these projects. The support can be additional encouragement through guidance documents and descriptions of exemplary practices, and grants to support regional planning for congestion pricing and managed lanes projects. The authors also pointed out that continued support was required for the enhancement of the modeling tools maintained by MPOs to improve their sensitivity to congestion pricing.

- In Ungemah et al. (2007), the authors consider ride-matching in the planning of carpool lanes. Ride-matching is planned by employers, transit organizations, and rideshare agencies, and enhanced through promotional activities by employers. They are most suitable in areas of high employment density. For ride-matching to be most successful, riders must (a) live close to each other, (b) travel long enough so that pickup time is relatively insignificant, (c) work together or close to one another, (d) have similar working hours, and (e) be consistent in carpool use.

- In Fischer et al. (2003), the authors address the issues regarding the planning and analysis of truck-only lanes on SR-60 and I-710 truck-only lanes in Southern California. SR-60 is an east–west corridor from downtown Los Angeles to Coachella Valley that is east of Los Angeles. SR-60 is one of the most heavily used corridors by trucks in Southern California because it runs through the warehouse and manufacturing districts of the San Gabriel Valley and Ontario International Airport. I-710 is the major access route from downtown Los Angeles to the ports of Los Angeles and Long Beach, where the combined port complex is the largest container port in the United States and the third-largest container port in the world. The study of these lanes suggests the following:

  - Truck lanes could improve freight mobility in congested urban areas, but with limited success. Identifying corridors with high truck-volumes is not sufficient for successful truck lanes because urban trucks generally make short trips during mid-day. So, truck-only or truck-toll lanes might not generate enough benefits compared with managed lane projects that allow multiple types of vehicles.
  - For extremely high-volume facilities which operate in congested conditions throughout most of the day, truck lanes may be feasible.
  - Truck lanes have the safety benefits of separating automobile and truck traffic.
  - Truck lanes accommodate overweight trucks or longer-combination vehicles (LCV). Such lanes could improve the economic efficiency of port drayage operations and provide the greatest stimulus for private investment in truck-lane facilities.

- In Chu and Meyer (2008), the authors identify the following criteria for potential truck-only toll lanes.

  - Candidate freeway lanes should have 2030 LOS E or F on the GP lanes during the PM peak period.
  - The 2030 daily truck volume on candidate freeways should be greater than 9,000.
  - The percentage of trucks on candidate freeways should be greater than 14%.
  - Candidate freeways should have at least 63 truck-related crashes per 100 million vehicle miles traveled (VMT).

- In Poole (2009), the author states that a cost-effective approach in planning for the separated roadway is to use rights of way that were created for other purposes (such as under-used railroads, drainage channels and power line corridors) and turn them into managed lanes. Upgrading current limited-access roadways for truck-only toll lanes would bring significant gains in productivity. However, the cost of thicker pavement and stronger bridges is seen as a barrier. Another important planning aspect for tolled roads is the values of time and reliability of car and truck drivers.

- In Wolshon and Lambert (2006), the authors report safety concerns that emerge when planning reversible roadway operations. These concerns include parking for enforcement vehicles, the difficulty to make emergency stops, and difficulties for service vehicles to access accidents. However, reversible operations usually do not result in more accidents.

2.1.4 Design and Regulations

The design and construction of managed freeway lanes involves a variety of improvements to widen or otherwise alter the existing roadway, including utility coordination and relocation, the installation of drainage systems, earthwork, paving, the construction of ramps, overpasses and bridges, and adding appropriate signage and striping. In some cases, new managed freeway lanes have been built within the median by removing shoulders. In others such as IH 10 in Houston and I-15 in San Diego, new right-of-way may be needed. In either case, modifications to some components of the existing roadway are likely.

2.1.4.1 Lane Design

Aside from new lane constructions, the conversion of an existing GP or HOV lane to a managed freeway lane can be less complicated if the prior design supports managed traffic without safety ramifications. About half of the HOV lanes in the United States meet the design standards commonly found in the AASHTO Green Book and AASHTO's 2004 Guide for High Occupancy Vehicle Facilities (AASHTO, 2004). However many projects were implemented with reduced lane and shoulder widths. In these instances, a safety analysis may be required to determine what design and/or operational changes are necessary to support changes in traffic volume after lane conversions. For added capacity, access locations of the new managed freeway lanes must be analyzed for safety and other reasons instead. TABLE 2.6 displays the basic cross-section elements for managed freeway lanes.

TABLE 2.6 Managed Freeway Lanes Cross-Section Specifications

Cross Section Element	Typical dimensions found in Professional Design Guidance
Lane Width	12 feet (3.7 meters)
Shoulder Width (Right and Left)	10 feet (3.0 meters) preferable 2 feet (0.6 meters) minimum (dependent on number of lanes, type of operation, sight distance) 14 feet (4.3 meters) for enforcement / apprehension
Buffer Width (if desired for non-barrier-separated operation)	2 to 4 feet (0.6 to 1.2 meters)
Sight Distance	Standard stopping sight distance for facility type
Safety considerations	Crash attenuation for exposed barrier ends Transition treatments with HOV or general-purpose lanes Adequate access opening lengths (minimum 1,200 feet [366 meters])

Source: AASHTO, *Guide for High Occupancy Vehicle (HOV) Facilities*, October 2004

Additionally, the physical configuration and operation of managed freeway lanes varies greatly because of travel demand and physical constraints. Managed freeway lanes may involve single or dual (or even greater) directional lanes operated on a concurrent (with the flow of traffic) or reversible-flow (inbound in the AM, outbound in the PM) basis. Concurrent operations typically provide one lane in each direction and these lane designs are symmetrically oriented around the median centerline. Reversible operations on freeways require full concrete barrier separation. See AASHTO (2004) for cross-sections for these configurations.

2.1.4.2 Access Control

Access limits entry to freeway lanes based upon facility congestion levels or operational conditions, such as an accident or maintenance needs. TABLE 2.7 lists the different types of access designs for freeway lanes.

TABLE 2.7 Types of Access Control for Freeway Lanes

Type of Access	Illustration
Weave Zones and Lanes are generally used on facilities with buffer separation. A weave zone refers to a short break in the buffer striping to allow for simultaneous ingress and egress. A weave lane is an entire lane designated for both ingress and egress between managed and GP lanes.	 Weave Zone Access Treatment on SR-167 Express Lanes in Seattle, WA
Slip ramps are separated ingress and egress using dedicated acceleration and deceleration lanes to provide drivers with a better opportunity to adjust their speed to match that of the traffic stream into which they are merging.	 Slip Ramp Access to the I-680 HOT Lane in Alameda County, CA

TABLE 2.7, continued

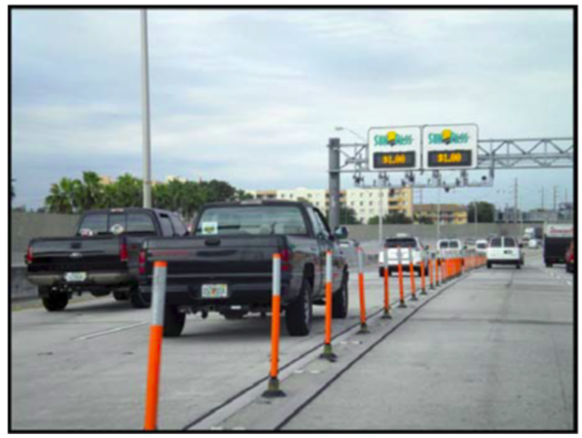
<table>
<tr>
<td>Near-continuous accesses are marked by dashed white-lines, while the rest of the express lanes are marked with double solid white-lines. The access points range from 3,000 to 9,000 feet long.</td>
<td>

Near Continuous Access on I-35W in Minneapolis</td>
</tr>
<tr>
<td>Grade-separated accesses are generally reserved for high volume movements and those serving linkages to transit facilities. They greatly reduce weaving and merging movements for vehicles entering or exiting a facility</td>
<td>
Direct Connector Ramp to HOV lanes in Los Angeles</td>
</tr>
</table>

2.1.4.3 Separation Treatments

The managed freeway lanes currently in operation typically utilize painted buffers, pylons, or concrete barriers to separate the managed lanes from the GP lanes and designate entry and exit points (see FIGURE 2.5).

Concrete barrier separation on I-25 Express in Denver



Pylon separation on the I-95 Express in Miami

FIGURE 2.5 Types of Separation Treatments

2.1.4.4 Tolling Provisions

PM freeway lanes rely on electronic-toll-collection (ETC) systems for the collection and processing of toll payments (see FIGURE 2.6). ETC keeps traffic flowing by allowing motorists to pay tolls without having to stop. In the United States, most of ETC systems use radio-frequency identification (RFID) technology communicating in the 815 MHz frequency range. While no national interoperability standard has emerged, MAP-21 passed in July 2012 calls for all toll facilities on federal-aid highways to implement technologies and business practices that facilitate the interoperability of ETC systems.

RFID reader antennae

Windshield-mounted ETC transponder

FIGURE 2.6 Components of an Electronic Toll Collection System

In addition to basic ETC components, most managed freeway lanes also utilize photo-enforcement systems to increase accuracy and reduce the chance of missed transactions. Since RFID systems are susceptible to miss transactions due to a variety of environmental conditions, video enforcement is one way of protecting revenue streams and ensuring that most trips, if not all, result in paid transactions.

2.1.4.5 Signage

Accurate, informative signs are essential in explaining operational procedures of managed freeway lanes and ensuring safe access and egress from them (see FIGURE 2.7 to FIGURE 2.9). Signs for these lanes should provide motorists with the following information:

- Access and egress locations
- Distances to ramps
- Occupancy requirements
- Operating hours
- Tolls, if any
- Enforcement issues

In addition, motorists must be given adequate time to decide whether to use and access the managed freeway lane safely. Motorists must be able to make informed and real-time decisions on whether to use the facility. Signage should adhere to the standards prescribed for special-use facilities in the federal Manual on Uniform Traffic Control Devices (2009 edition) Section 2B-49 and 50.

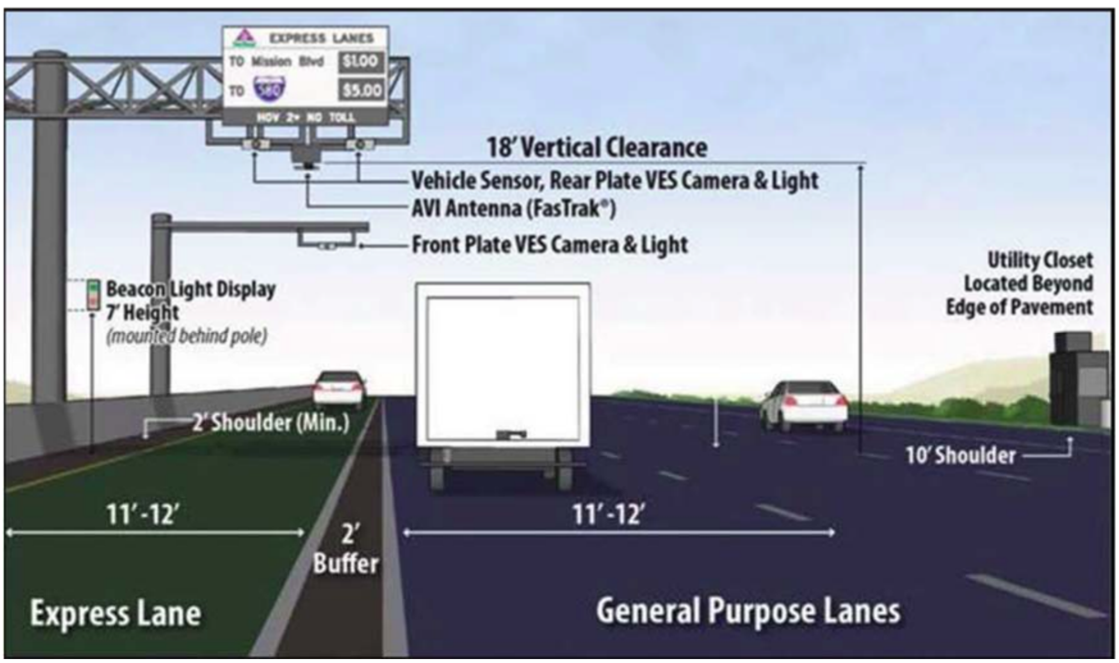


FIGURE 2.7 Typical Design for Signage for Managed Freeway Lanes

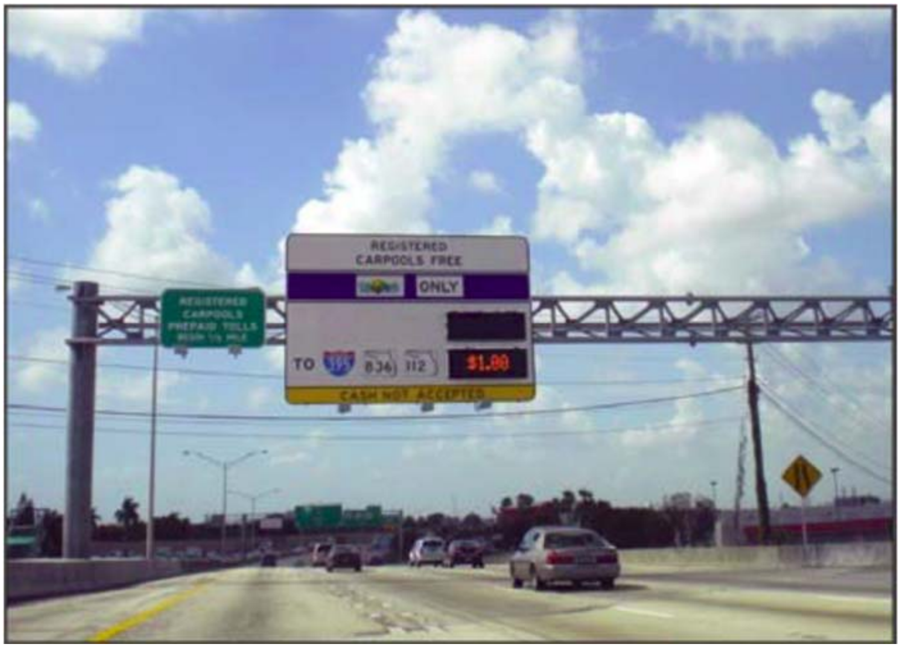


FIGURE 2.8 Variable Message Sign on I-95 Express in Miami

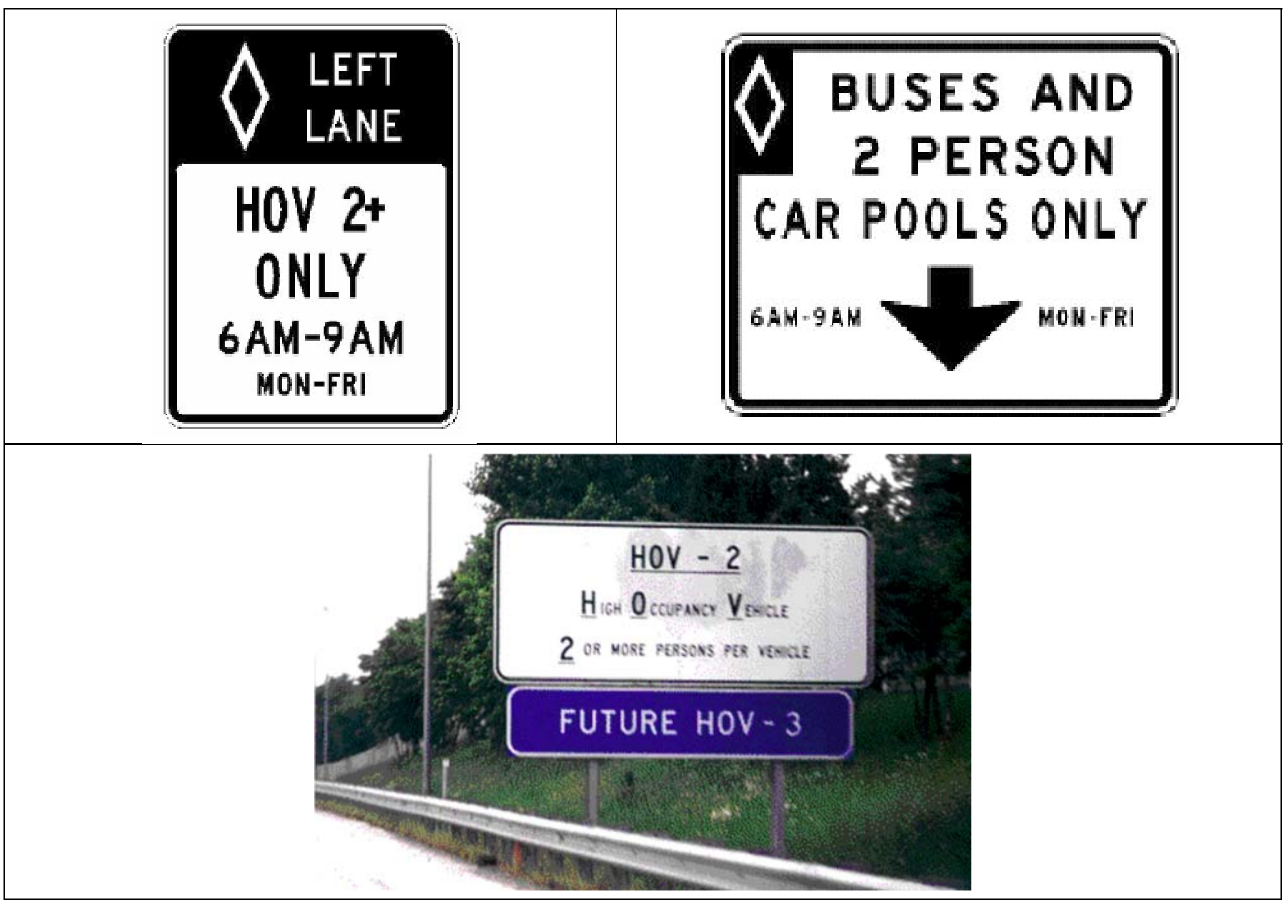


FIGURE 2.9 Signs for HOV Lanes

2.1.4.6 Enforcement Areas

Managed freeway lanes should include locations from which enforcement officers can monitor traffic and identify unauthorized vehicles (see FIGURE 2.10). In order to see occupants properly during hours of darkness or inclement weather, lighting is required at observation points. The enforcement areas should be large enough to accommodate the need for enforcement officers to accelerate to the speed limit before entering traffic. The areas should be wide enough to accommodate safety enforcement action and may be located near tolling points, allowing officers to monitor traffic as it enters the facility and provide a visual deterrent to potential offenders.

FIGURE 2.10 Enforcement Area on I-45 in Houston

2.1.4.7 Rules and/or Regulations

Vehicle occupancy verification is critical in the implementation of managed freeway lanes. Currently, vehicle occupancy verification depends primarily on manual methods with direct visual observation by enforcement personnel (Ungemah et al., 2008). Stationary and roving patrols work together to monitor managed freeway lanes and apprehend violators. The cost of this manual method is high, especially for HOT lanes.

There are two main automated vehicle occupancy enforcement systems, roadside systems and in-vehicle systems. Roadside systems use surveillance equipment to capture images of the interiors of passing vehicles. Expensive imaging devices are required to capture details from the interiors of fast-moving vehicles. In-vehicle systems verify the number of vehicle occupants using advanced airbag systems to distinguish empty seats from occupied ones. Both systems require vehicle infrastructure integration (VII) to communicate the occupancy information from vehicles to the roadside infrastructure. In-vehicle systems face two key obstacles. One is that motorists and automobile manufacturers may be reluctant to allow occupancy information from airbag systems to be transmitted to the roadside infrastructure because many consider such information private. The other obstacle is the length of time required for every vehicle to be equipped with the technology.

There are currently two methods to determining occupancy violations. One is to photograph a frontal view of the vehicle and driver with sufficient quality to determine the identity of the driver. The other is to capture images of the vehicle's license plate. Both systems have issues. First, the photographic record of occupants may be used for other purposes. Second, VII must maintain anonymity of the vehicles and drivers in violation and prevent specific vehicles from being tracked. Third, HOV infractions are considered as moving violations and result in assessment of points on the driving record in many states.

For photo enforcement, the operation must maintain a high level of oversight and cameras must be inspected periodically (Kiesling and Ridgway, 2006). Elements necessary for oversight include conducting periodical visits to the vendor's operations facility, providing clear business rules to the vendor, auditing the issuance of unauthorized or unapproved citations, making misuse of images a breach of contract, making sure records are confidential, limiting the time images are kept, and periodically conducting technical inspections of cameras.

For HOT lanes, manual and automated occupancy enforcements have limitations (Poole, 2011). Many HOT lanes lack space for separate enforcement lanes or for patrol officers. Both roadside and airbag deployment systems can detect only front-seat passengers, while back-seat occupant verification is important in determining tolls for HOT lanes.

2.1.5 Public Acceptance

The issues concerning public acceptance of managed freeway lanes include the following: (Perez et al., 2012)

- **Project Benefits and Goals**: As with any investment of public funds, constituents and stakeholder groups have an immediate interest in the benefits that a managed freeway lane may bring and why it is the best solution to address a given problem. Ungemah and Collier (2007) studied the pre- and post-implementation public opinion concerning tolling and pricing in California (SR-91 Express lanes and I-15 FasTrak HOT lanes), in Texas (all toll lanes), and Minnesota (I-394 MnPASS HOT lanes). In all cases, the public was skeptical and even opposed these projects initially. With careful and judicious planning, post-implementation feedback was positive in all three states. For a pricing project to be politically acceptable, Ungemah and Collier (2007) recommend that the project should be simple in design, progress in an incremental step, and earn public trust by having a transparent financial flow.

- **Travel Impacts:**
  - Perez et al., (2012) report that very few drivers choose to use the PM freeway lanes all the time. Instead, users may choose to pay to use the lanes when they want to guarantee their trip time or avoid congestion. At other times, drivers will choose the GP lanes during congested conditions to avoid paying a toll. Frequent users of managed lanes make many trips on the free GP lanes or choose alternate modes like transit on certain days.

- In Golob (2001), 86% of 457 FasTrak customers on I-15 in San Diego, a HOT-Lane project with two reversible lanes, travel in-bound on the HOT lane at least once during a week, 35% drive solo at least once on GP lanes, and 11% make at least one trip in carpools.
- In Li et al. (2007), carpoolers and solo drivers in Dallas-Fort Worth and Houston, Texas rate the ability to use HOV lanes the most important factor among the reasons for forming carpools in the study. Traveling with others was considered enjoyable and ranked second. Carpool-partner matching program and preferred parking at work were the least important factors in making the mode choice decision. Other factors mentioned by survey respondents include timesaving, helping the environment and society, and sharing vehicle costs. The reasons for not carpooling include the limitation of location and schedule for carpooling, flexibility of driving alone, and the need to use vehicle during the day.

- **<u>Project Cost and Use of Funds</u>**: While tolls are not popular, experience with existing PM freeway lanes demonstrates that these projects are likely to generate greater support with the public when toll revenues are used to support the maintenance and operations of the project and other transportation needs such as transit improvements (Perez, et al., 2012).

- **<u>Equity and Fairness</u>**: Because PM freeway lanes provide paying drivers the opportunity to bypass congestion, these facilities to some critics favor higher income individuals. Below are results from several surveys and studies.
  - In Golob (2001), carpoolers think that FasTrak, the HOT-lane program on I-15 in San Diego, is less fair and effective. However, the opinion regarding effectiveness of the program varied across the survey population. Educated customers are more likely to think the program is effective. Those younger, older, or more restricted to carpools by household character perceive the program less effective.
  - In Harrington et al. (2001), the authors surmise that public aversion is primarily from two reasons. One reason is that many perceive the collected fees as an additional tax and the other is that the imposition of congestion fees unfairly penalizes those who cannot participate in carpool programs because of household locations and occupational decisions. Survey respondents from Southern California were described as a “congestion fee” of 5 to 10 cents per mile (depending on current congestion levels) was to be levied on all freeways in the region. Then, respondents were asked to evaluate the congestion fee with the following options:
    - <u>Congestion fees with tax reductions</u>: Respondents were told that a certain portion of the fee revenues (25%, 50% or 82%) would be used to reduce other taxes, such as sales tax or state gasoline taxes or DMV registration and license fees. They were also given a dollar amount of the tax reduction.
    - <u>Congestion fees with coupons</u>: Respondents were told that they would be given coupons that could be used for a variety of transportation-related services, including public or private transit, jitney services, vehicle emission equipment repair, etc. The face values of the coupons being offered were 25%, 50% or 82% of the respondent's estimated fee payments.

- Congestion fees only on the left-most lanes: Respondents were asked if they would support a policy in which fees would be charged only on the left-most lane of all freeways.

  When offered with tax reduction, the support for congestion fee increases from 43% to 50% on average. For the option with coupons, the support decreases slightly. When only imposed on the left-most lanes, the support of the fees increases from 37% to 46%, instead. Harrington et al. (2001) conclude that the public will respond favorably when the congestion pricing proposals preserve motorist choice and address the issues of revenue redistribution.

  - In Weinstein and Sciara (2006), the analysis suggests that (a) HOT lane projects always raise equity concerns, (b) assessing project's distributional outcomes should be a part of every step of the planning process, and (c) impacts on low-income travelers are complicated. Weinstein and Sciara (2006) recommend public education/outreach, incorporating equity analysis into the planning process, designing HOT lanes as pilot projects, and using HOT revenue to address inequity. The authors point out that travelers with low-income may be unable to acquire a transponder because they do not have a credit card or bank account.
  - Taylor and Kalauskas (2010) suggest four strategies to mitigate equity concerns and overcome political opposition. These include (1) addressing equity early in process, (2) building broad-based support from the public and interest groups, (3) establishing trust between elected officials and transportation agencies, and (4) getting powerful constituencies for toll revenues.
  - In Dill and Weinstein (2007), truck-only toll and HOT lanes were the only projects with more than 50% support among the survey respondents. Women are likely to support truck-only toll lanes because they may have a stronger preference to have trucks separated from personal vehicles. Residents in regions that have tolled facilities are supportive of pricing projects. For example, 60% of the residents Los Angeles County, the region with the only HOT lanes in California, support HOT lanes whereas approximately 50% of residents in other regions do the same.

- **Technology Concerns**: Electronic toll collection is standard in the United States, known in different regions by brand names such as E-ZPass and FasTrak®. The public needs to be informed of how the proposed ETC system will work, including the role of an electronic transponder, the function of entry and exit gantries, the administration of pass-holder accounts, and the protection of individual privacy. (Perez et al., 2012)

- **Enforcement:** The traveling public wants information on how the managed freeway lanes will be enforcement (e.g., see FIGURE 2.11). A lack of upfront coordination could lead to misinformation and changes that could be detrimental to public support. (Perez et al., 2012)

FIGURE 2.11 HOV Violation Sign

2.1.6 Environmental Considerations

Vehicle emissions are the main environmental issue with managed freeway lanes. The literature regarding to vehicle emissions on managed freeway lanes are limited and most rely on computer simulation or modeling software. As discussed below, they can provide insights on how managed freeway lane can benefit environment by reducing greenhouse gases.

2.1.6.1 HOV and HOT Freeway Lanes

HOV freeway lanes can reduce vehicle emissions because HOVs carry more passengers and spend less time in uncongested HOV freeway lanes. These lanes can also reduce emissions resulting from initial inefficient engine operation at the beginning of a trip and evaporation of fuel from a hot engine when the trip ends. Boriboonsomsin and Barth (2008) compare continuous and limited-access HOV freeway lanes in terms of vehicle emissions. The authors' simulation model suggests that continuous-access HOV freeway lanes produce less emission than the limited-access type. When compared to the latter, continuous-access lanes produce about 12 – 17% less CO, 7 – 13% less HC, and 3 – 8% less NO_x and CO_2. The concentrated weaving behavior at designated ingress and egress locations for limited-access HOV freeway lanes seem to generate more emissions. Drivers frequently have to slow down and wait for gap in the adjacent lane or accelerate to take the gap ahead. These actions also cause other vehicles to react in fashions that generate more vehicle emissions as well. For continuous-access lanes, drivers have unlimited opportunity to change lane and are less likely to make quick acceleration or deceleration, thereby generating less vehicle emissions.

2.1.6.2 Truck-Only Toll Freeway Lanes

Trucks have higher carbon dioxide emission factors than light-duty vehicles. The total amount of carbon dioxide emissions from trucks is only second to passenger cars. Truck-only toll lanes can reduce greenhouse gases emissions because they generally have less congestion and better traffic flow, both of which improve fuel efficiency. In Chu and Meyer (2009), the authors' demonstrate using a computer simulation demonstrates that, when compared to those without truck-only toll lane, scenarios with truck-only toll lanes reduce HC emission by approximately 10%, NO_x emission by 18% on average, and CO_2 emission by at least 50%.

Many use environmental considerations to argue against truck-only lanes because trucks typically use diesel engines. These engines have high emission factors. However, modern trucks have to comply with new low-sulfur diesel fuel standards and all trucks sold after 2007 must use new low-emission diesel truck engines (Poole, 2009). When coupled with the increase in trucking productivity, the socio-economic costs of moving goods by trucks are lower than rail.

2.1.7 Traffic Conditions and Facility Performance

This section addresses the effects of managed freeway lane on traffic conditions and safety.

2.1.7.1 Effects on Traffic Conditions

HOV Freeway Lanes: In Liu et al. (2011a), the authors conclude that GP lanes are more likely to breakdown than HOV freeway lanes. This supports the notion that HOV freeway lanes save time and provide reliable travel-times. On freeways with open queues, HOV freeway lanes can reduce person-hours of travel without significantly increasing vehicle-hours of travel. However, converting GP to HOV freeway lanes can reduce freeway's ability to store vehicles, extend freeway queues and block ramps (Daganzo and Cassidy, 2008). Liu et al. (2011b) also report that (a) concrete barriers lead to the most isolation, (b) soft-barrier separation has more interaction, and (c) congested GP lanes create "frictional" effects on HOV lanes when they are buffer-separated. Menendez and Daganzo (2007) on the other hand find that an HOV lane has no drastic lane-changing effect on adjacent GP lanes. Cassidy et al. (2010) show that ineligible vehicles migrate from the HOV lane when the HOV restriction becomes effective. This reduces the lane-changing rate before a bottleneck. However, lifting and imposing HOV restrictions can cause a bottleneck to remain active for at least 30 minutes.

HOT Freeway Lanes: Liu et al. (2011a) demonstrate that HOT freeway lanes preserve travel-time reliability and save time like HOV freeway lanes. Burris et al. (2012) and Munnich and Buckeye (2007) both study MnPASS, a HOT freeway lane in Minnesota. The former finds that MnPASS save minimal time and its toll rates change frequently. The latter conclude that MnPASS reduces congestion on the entire corridor. Safirova et al. (2003) report that converting HOV freeway lanes in Northern Virginia to HOT freeway lanes would reduce congestion on GP lanes, while the congestion on the converted lane may increase slightly.

Truck-only Lanes: Rakha et al. (2005) write that not allowing trucks to use left lanes on steep grades may decrease traffic density and number of lane changes. On the other hand, restricting trucks to the right-most lane can increase the number of lane-changes at locations with no entry or exit ramps. The report also notes that location characteristics influence the effects of truck restrictions and trucks should not be allowed in the left-most lane if the grade is steeper than 4%.

2.1.7.2 Safety Implications

Chung et al. (2007) find that a greater percentage of collisions occurred in the left-most lanes adjacent to HOV freeway lanes than any other lane. This suggests that restricting the number of entrances and exits for HOV freeway lanes can make lane-changing actions more intense and challenging and perhaps leads to more collisions near HOV freeway lanes. However, the overall accident rate on MnPASS, a HOT freeway lanes separated with double solid white-lines in Minnesota, dropped after the conversion (Munnich and Buckeye, 2007).

Crash data from the New Jersey dual-dual turnpike show that 45% of sideswipe collisions involve trucks and, while generating only 30% of traffic, trucks account for 40% of crashes on mixed lanes (Middleton and Lord, 2005). Lord et al. (2005) also support the notion that truck-free freeway facilities have a better safety record than mixed-traffic facilities. In Vidunas and Hoel (1997), results from a computer simulation implies that truck-free freeways would be safer and truck-only facilities would improve operations and safety.

2.2 Managed Arterial-Lanes

In the literature, the number of publications and case studies discussing managed lanes on arterials is less than the ones on freeways. This is particularly evident for publications appearing in 2000 and afterward. Below, we highlight the difference between managed lanes on freeways and arterials. As previously explained, the operating environment on arterials is different. Arterials deliver traffic from collector roads to freeways/expressways and between urban centers. By nature, they have many intersections with vehicles of various types both making stops and traveling at different speeds. Speed limits on arterials are between 35 and 50 mph, instead of 55 and 70 mph.

In this section, we use the term “facilities” instead of “lanes,” where the former refers to individual roads and lanes therein as well as treatments such as queue jumps or bypasses. Similar to before, we group the managed facilities on arterials into two main categories, one managed by eligibility and the other by price and eligibility. We refer to facilities in these two categories as EM and PM arterial facilities. EM arterial facilities include HOV and bus-only lanes along with any specialized treatments, e.g., at signalized intersections. As in freeway lanes, we view PM arterial facilities as those EM arterial facilities that allow ineligible vehicles to use the facilities for a fee. Although truck-only toll lanes are part of the PM freeway lanes, we do not include the lanes in this section. According to Samuel et al. (2002), “the most likely early candidates are interstate highways with heavy truck traffic that need additional capacity to cope with projected growth” and we do not envision heavy truck traffic on arterials.

2.2.1 Policies and Practices

The policies of HOV and HOT are similar to those for freeway lanes in Section 2.1.1. For bus-only lanes and special lane treatments, the policy is to enhance transit service by providing faster transit service and improving travel-time reliability. TABLE 2.8 and TABLE 2.9 provide examples of managed arterial facilities in the United States and Canada.

TABLE 2.8 HOV Lanes on Arterials in the United States and Canada

Name	Information and Statistics
Montague Expressway	• Type: Concurrent flow HOV lane • Location: Santa Clara, California • Year opened: 1983 • Length: 5.4 miles • Occupancy requirement: 2+ • Violation rates: – 34% (AM) and 22% (PM) at intersection of Zanker Road – 61% (AM) and 64% (PM) at intersection of Trade Zone Blvd • Vehicles using HOV lane at peak hour: 188 (AM), 235 (PM) • Vehicles using GP lanes at peak hour: 1,732 (AM), 1,336 (PM)
Hastings Street	• Type: Concurrent flow HOV lane • Location: Vancouver, British Columbia • Year opened: 1996 • Length: 4.4 miles • Occupancy requirement: 2+ • Violation rate: 13% (AM)
Eglinton Avenue	• Type: Concurrent flow HOV lane • Location: Toronto, Ontario • Year opened: 1993 • Length: 7 miles • Occupancy requirement: 3+ • Violation rate: > 32% (AM)
South Dixie Highway (U.S. 1)	• Type: Concurrent flow HOV lane • Location: Miami, Florida • Year opened: 1974 • Length: 5.5 miles • Occupancy requirement: 3+ • Violation rate: 8%
Santa Fe Drive	• Type: Concurrent flow HOV lane • Location: Denver, Colorado • Year opened: 1986 • Length: 7.5 miles (northbound), 5.7 miles (southbound) • Occupancy requirement: 2+ • Lane of road used: left lane

TABLE 2.8, continued

Kalanianaole Highway	• Type: Contraflow HOV lane • Location: Honolulu, Hawaii • Year opened: 1975 • Length: 2.4 miles (1.9 miles contraflow, 0.5 miles concurrent flow) • Occupancy requirement: 3+ • Violation rate: 9%
Union Avenue	• Type: Reversible HOV lane • Location: Memphis, Tennessee • Road configuration: 4 lanes in major flow direction, 2 lanes in minor flow direction
Nicholasville Road (U.S. 27)	• Type: Reversible HOV lane • Location: Lexington, Kentucky • Road configuration: 3 lanes in major flow direction, 1 lane in minor flow direction, 1 two-way left-turn lane

TABLE 2.9 Bus Facilities in the United States and Canada

Location	Street	Length	Bus Volume
Bus Street/ Malls			
Denver	16th Street [a]	1 mile	70 second headways
Minneapolis	Nicolett Avenue	11 blocks	820 daily bus trips
New York City	49th-50th [b]	0.88 miles	230 daily bus trips
Portland (Oregon)	5th Avenue [c]	0.65 miles	175 peak hour
	6th Avenue [c]	0.65 miles	120 peak hour
Contraflow Bus Lanes			
Los Angeles	Spring Street	1.5 miles	140-150 peak hour
Minneapolis	Marquette Avenue	12 blocks	100-120 peak hour
	Second Avenue	12 blocks	100-120 peak hour
	Hennepin Avenue	12 blocks	100-120 peak hour
New York City	2nd Avenue	0.1 miles	240 4:00-7:00 PM
Pittsburgh	Fifth Avenue	n/a	70-100 peak hour
	Wood Street	n/a	70-100 peak hour
	Smithfield Street	n/a	70-100 peak hour
Concurrent Flow Bus Lanes			
Chicago	Madison Street	0.9 miles	25-45 peak hour
Houston	Milam Street	0.6 miles	100 peak hour
	Main Street	1.1 miles	70 peak hour
Newark	Broad Street	1.3 miles	100-150 peak hour
New York City	Madison Avenue [c]	0.85 miles	150-180 peak hour
	Fifth Avenue	1.3 miles	165-195 peak hour
	Broadway	0.7 miles	100-150 peak hour
	Lexington Avenue	1.5 miles	60 peak hour
Ottawa	Rideau Street	0.4 miles	45-60 peak hour
	Albert Street	1.0 miles	165-200 peak hour
	Slater Street	1.0 miles	165-200 peak hour
San Francisco	Geary Street	1.1 miles	20-30 peak hour
	Mission Street	1.7 miles	30-50 peak hour
Toronto	Bay Street	1.6 miles	25-40 peak hour
	Pape Avenue [d]	n/a	25-100 peak hour
	Eglington Avenue [d]	1.9 miles	45-50 peak hour
	Allen Road [d]	n/a	25 peak hour
	Lansdown Avenue	0.9 miles	25 peak hour
Tucson	Broadway Boulevard	5 miles	8-10 peak hour
	22nd Street	3 miles	20-25 peak hour

Notes: [a] Shuttle buses operate on Denver Mall; regular route buses operate on other facilities.
[b] Buses and taxis operate on the 49th-50th Street transitways from 11 AM-4 PM weekdays.
[c] Dual bus lanes.
[d] Opened to 3+ HOVs in addition to buses.

Sources: Monahan (1990), New York City DOT (1983), Parsons Brinckerhoff (1991), Phillips (1997), St. Jacques and Levinso (1997), Turnbull (1994), Municipality of Metropolitan Toronto (1997).

2.2.2 Planning and Implementation

In general, the planning and implementation of managed arterial facilities are similar to those for freeway lanes in Section 2.1.3. Below is a summary of publications that address planning and implementation of arterial facilities.

Nihan and Davis (1990) report that successful implementations of HOV lanes on arterials occurred on those with high volume, limited access, and suburban commuter corridors. The degree of success depends on the ability to achieve the same level of control as the freeways. To be successful, arterials with HOV lanes should have minimal turning movements, signalized intersections, and access to abutting properties. Spot treatments such as queue jumps play an important role, particularly at recurrent bottlenecks, overloaded intersections, and system constrictors such as tunnels and bridges. Nihan and Davis (1990) also group HOV lanes on arterials into three main groups: (a) HOVs on principal arterials; (b) HOVs on minor arterials; and (c) spot treatments such as queue jumps.

According to Turnbull (2002), the following groups/agencies should be involved in the planning and designing of managed lanes on arterials. Although the discussion in Turnbull (2002) focuses on HOV and bus lanes, the conclusions also apply to other forms of managed lanes on arterials.

- <u>Local Municipalities</u>: City or county departments may have the lead responsibility on managed facilities on arterials. For HOV lanes, the city or county may be the lead agency that is responsible for all aspects of a project such as planning, designing, implementing, operating, and maintaining the managed facility. For bus-only lanes, it may be more appropriate for a transit agency (see below) to take the lead instead.

- <u>Transit Agency</u>: A transit agency may have the lead responsibility on managed facilities such as bus-only lanes or may co-sponsor a HOV-lane project. Transit agencies usually work closely with the local municipality or state department of transportation that has jurisdiction over the street and traffic signal systems. Key responsibilities of transit agencies may focus on planning and designing for bus operations, enforcement, and overall project coordination.

- <u>State Department of Transportation (DOT)</u>: The state will usually have the lead role with managed lanes projects on state-owned arterials. On the other hand, the state DOT may be a supporting agency when the project provides a link to and from, e.g., HOV lanes on freeways. Representatives from the state DOT may be involved in a multi-agency team or may provide assistance throughout the development, implementation, and operation of managed facilities on arterials.

- <u>Local and State Police</u>: Representative from the state, city, and county police departments should be involved in the development of managed-facility projects. One or more of these agencies are usually responsible for enforcing the rules of the managed facility.

- <u>Rideshare Agency</u>: If managed facilities are open to carpools and vanpools, the rideshare agency is usually included as a member of the multi-agency team.

- MPO: Representatives from the MPO may participate on the multi-agency team and may provide assistance depending on the nature and scope of the managed facility.

- Federal Agencies: The FHWA and FTA may partially fund the project and may wish to be involved and/or monitor the managed-facility project.

- Other Groups: In some cases, it may be appropriate to include representatives from the following:

  - The local judicial system responsible for enforcing fines and citations.
  - Personnel from emergency agencies such EMS and the fire department who have to respond to incidence and accidents on arterials.
  - Tow truck operators who may be responsible for removing disable vehicles.
  - Businesses, delivery companies and vendors, and neighborhood groups.

2.2.3 Design and Regulation

Each bullet point below addresses the design of managed arterial facilities. Other aspects of the design and regulation are similar to those for managed freeway lanes in Section 2.1.4.

- HOV and HOT Lanes: The design of HOV and HOT lanes on arterials are similar to those on freeways and operates on a concurrent, reversible, or contraflow basis. The latter typically applies to one-way streets. Like those on freeways, HOV and HOT on arterials are typically implemented on the left-most lanes on two-way streets and on center lanes when the flow is reversible.

- Bus-only or Bus-Toll Lanes: TABLE 2.10 lists the different designs of bus-only lanes on arterials and discusses their strengths and weaknesses. The designs using median and curb-side lanes, where the latter are with contraflow operations on one-way streets, are also suitable of bus-toll lanes. In addition to those in TABLE 2.10, there are also designs for bus-only or bus-toll lanes are off-street (see FIGURE 2.12).

TABLE 2.10 Strengths and Weaknesses of Different Bus-Only Lane Designs

Type of Bus-only Lanes	Strengths	Weaknesses
Curb-side: concurrent flow	Ease of installation; Low cost; Minimize street space devoted to bus system.	Difficult to enforce; Least effective in reducing bus travel-time; Added delay for buses due to conflicts between right-turning traffic and pedestrians
Curb-side: contraflow	Enables two-way bus operation on one-way streets; May increase number of curb faces available for passenger stops; Completely separate bus from general traffic flow; Self enforcing	May disperse BRT onto several streets and reduce passenger convenience; Limits passing opportunities around stopped or disabled buses unless multiple lanes are provided; Can create conflict with opposing left turns; May create safety problems for pedestrians
Interior Lanes: concurrent flow	Remove BRT from curbside frictions; Allow curb parking to be retained; Provide far-side bus "bulbs" at stops for passenger convenience	Require curb-to-curb street widths of 60 to 70 feet; Curb parking maneuvers could delay buses
Median Lanes: concurrent or contraflow	Physically separates BRT running ways from general traffic; Provides a strong sense of bus identity; Eliminates conflicts between buses and right-turning automobiles; Can enable bus lanes to be grade separated at major intersections	Require prohibiting left turns from the parallel roadways or providing special lanes and signal phases for these turns; Require wide streets, generally more than 80 feet from curb to curb; Costs can be high
Bus-only streets or bus malls	Remove BRT from general traffic; Increase walking space for pedestrians and waiting space at stops/stations; Improves BRT identity; Improves the ambience of surrounding areas	Require nearby parallel streets for displaced traffic, provisions for goods delivery and service access from cross streets or off-street facilities; Generally limited to a few city blocks

FIGURE 2.12 Off-Street Bus-Toll Lanes

Turnbull (2002) suggests the following general guidelines regarding traffic volumes for various designs or implementations of managed facilities.

TABLE 2.11 Guidelines for Bus-Only and HOV Lanes

Type	Minimum Traffic Volume
Bus Mall	80 – 100 vphpl*
Bus-Only Lane (Left or Right-side)	50 – 80 vphpl
Contraflow Bus-Lane on one-Way Street	50 – 80 vphpl
HOV Lanes (Left or Right-side)	200 – 400 vphpl
HOV Lanes (Center and Two Way)	200 – 400 vphpl
HOV Lanes (Center and Reversible)	80 – 160 vphpl

*vphpl = vehicles per hour per lane

- **Priority Treatments at Intersections**: In the literature, there are many treatments giving priorities to, e.g., buses and HOVs, when traveling through signalized intersections. Names for these treatments vary depending on the author(s) of each report or journal article. Below are some of the more common treatments.
  - Queue Jump at Signalized Intersections: Some also refer to these lanes as "signal-preemption lanes" or "at-grade queue jumps." (see FIGURE 2.13) In principle, these lanes are short lanes at the approach of an intersection reserved for eligible vehicles such buses or HOVs. These lanes have a separate traffic signal head and an advance green light, while holding the general-purpose lanes on red. Doing so allows buses and HOVs

to move through the intersection and re-enter managed or general-purpose lanes in advance of other traffic.

FIGURE 2.13 At-Grade Queue Jump

– Bus Advance Areas or Gating: Turnbull (2002) describes a bus advance area as a segment of road before a signalized intersection. A set of pre-signals are used to hold other traffic while allowing buses to move to the front of the traffic stream at the intersection. This concept is being tested in London, England and Berne, Switzerland.

– Priority Signal Treatments: A number of different techniques and technologies can be used to provide, e.g., buses with priority at signalized intersections. Most implementation involves technologies that communicate with the signal controller to, e.g., change the signal phasing.

– Grade-Separated Queue Jumps: These refer to overpasses and underpasses at signalized intersections. (see FIGURE 2.14 and FIGURE **2.15**) Such queue jumps allow eligible vehicles to travel through the intersection without having to wait for green lights. In Poole and Swenson (2012), the authors recommend that grade separated-queue jumps should be used for the heaviest through movements of two intersecting roadways.

Source: Swenson and Poole (2012)

FIGURE 2.14 Grade-Separated Queue Jumps or Overpass at an Intersection

Source: Swenson and Poole (2012)

FIGURE 2.15 Grade-Separated Queue Jumps or Underpass at an Intersection

2.2.4 Public Acceptance

As recommended in Nihan and Davis (1990), community involvement is important in HOV projects on arterials because they tend to benefit some and burden others. In Orange County, California, 75% of survey respondents expressed positive attitudes toward an HOV lane "test" on arterials. Although they felt that a GP lane may be a more effective congestion mitigation solution, they were willing to try HOV lanes (Green and Barasch, 1986). In one survey (Gilmore Research Group, 1988), 90% of survey respondents in Seattle were either somewhat or strongly support the idea of bus and carpool lanes. In another (Rutherford, 1989), 99% of people were aware of HOV lanes and 80% did not think that they were unfair to non-users.

2.2.5 Environmental Considerations

The impacts of managed arterial facilities on the environment are similar to those for freeways in Section 2.1.6.

2.2.6 Traffic Conditions and Facility Performances

The performance of HOV facilities on arterials has been mixed (see TABLE 2.12). Among the 95 HOV facilities on arterials reported in Batz (1986), 22 of these facilities were suspended because of low utilization (11), reconstruction of roadways (5) and enforcement problems (6). Eleven other projects had enforcement problems and were in danger of being suspended. Among successful facilities, only 33 could provide data that showed (a) increased carpool and transit use, (b) reduced congestion, and (c) decreased travel times. On the other hand, a contraflow bus-only lane in downtown Chicago was suspended following pedestrian deaths. Crowel (1978) states that curb-side bus-only lanes on arterials have been known to increase transit travel times. Similarly, the priority signal treatments also had little effects on buses under mixed traffic conditions. Batz (1986) reports that nine out of 16 priority signal treatments in his review were suspended because of delays caused to other traffic, high maintenance costs, and other unspecified reasons. Later, Environmental Protection Agency (2000) reports that bus-only lanes in New York City saved up to 30 minutes in travel times, increased the ridership of some bus lines by 7%, and significantly improved on-time performance of those bus lines using the bus-only lanes.

In other studies, Henry and Mehyar (1989) reported that non-barrier-separated HOV facilities can be operated safely. Golob et al. (1989) reports that there is no measurable increase in accident frequencies could be attributed to a non-barrier-separated HOV lane in Los Angeles. Mounce (1984) reports that the violation of a non-enforced priority ramp in Houston was 40% or higher and enforcement may not be cost effective when the violation rate is low. Billheimer et al. (1981) indicates that the base violation rate before adopting an enforcement strategy should be between 5% and 12%.

TABLE 2.12 Performance of Arterial Facilities in the United States and Canada

Facility	Findings
Montague Expressway • Arterial HOV lane • Location: Santa Clara, California • Year opened: 1983 • Length: 5.4 miles • Occupancy requirement: 2+	• Violation rates: – 34% (AM) and 22% (PM) at intersection of Zanker Road – 61% (AM) and 64% (PM) at intersection of Trade Zone Blvd • Vehicles using HOV lane at peak hour: 188 (AM), 235 (PM) • Vehicles using GP lanes at peak hour: 1,732 (AM), 1,336 (PM) • HOV lane users lost travel time compared to users of general GP lanes. • Entire roadway operates at LOS F. • High violation rates due largely to lack of access control along expressway. • Lessons learned: – Lack of access control and close spacing of intersections and freeway on-ramps along an HOV lane can lead to frequent violation of the HOV lane. – If an arterial HOV lane runs parallel to a freeway HOV lane, the greater travel time savings achieved by the freeway lane over long distances could undermine the usefulness of the arterial HOV lane. – The effectiveness of a curbside HOV lane is diminished when large numbers of right-turning vehicles must share the HOV lane.
Hastings Street 1: • Facility statistics: • Type: Arterial HOV lane • Location: Vancouver, British Columbia • Year opened: 1996 • Length: 4.4 miles • Occupancy requirement: 2+	• Violation rate: 13% (AM) • Seven months after opening of HOV lane, substantial changes seen in AM peak hour traffic: • Overall traffic volume increased by 10%. • Two person carpools increased by 40%. • Three or more person carpools increased by 28%. • Average vehicle occupancy increased from 1.27 to 1.33. • HOV lane produced travel time savings of 3-5 minutes.

TABLE 2.12, continued

Eglinton Avenue • Type: Arterial HOV lane • Location: Toronto, Ontario • Year opened: 1993 • Length: 7 miles • Occupancy requirement: 3+	• Violation rate: > 32% (AM) • Buses saved 2.5-3 minutes on a 35 minute trip when using the HOV lane. • No substantial travel time savings for carpools and vanpools due to presence of buses. • HOV lanes carry 50% of total person volume on roadway. • Lesson learned: – HOVs may not realize travel time savings from HOV lanes if forced to share a lane with buses.
South Dixie Highway (U.S. 1) • Type: Arterial HOV lane • Location: Miami, Florida • Year opened: 1974 • Length: 5.5 miles • Occupancy requirement: 3+	Violation rate: 8% • HOV lane produced travel time savings of 5-10 minutes. • HOVs carry 40% of total person volume on roadway. • Vehicles move 7 mph faster in HOV lane than in the GP lanes. • HOV lane handles 24% of directional traffic. • Accident rate on roadway increased after implementation of HOV lane. • Lesson learned: – Implementing a managed lane may adversely affect the safety of an arterial roadway.
Santa Fe Drive • Type: Arterial HOV lane • Location: Denver, Colorado • Year opened: 1986 • Length: 7.5 miles (northbound), 5.7 miles (southbound) • Occupancy requirement: 2+ • Lane of road used: left lane	• HOV lane does not comply with FHWA guidelines, despite being implemented before the FHWA had guidelines regarding HOV lanes. • Colorado lacks design standards for arterial HOV lanes, complicating enforcement efforts. • Placement of HOV facility in the left lane makes maintenance difficult and hinders enforcement in places where traffic must cross the HOV lane to turn left. • HOV lane has no system of data collection, no benefit-cost analysis, and no ways of measuring the facility's success. • Enforcement of HOV lane is uneven across the municipalities that the lane passes through. • Lesson learned: – Effective implementation and management of managed lanes require adequate regulations, standards, and support from the state DOT.

TABLE 2.12, continued

Madison Avenue • Type: Arterial bus-only lanes • Location: New York, New York • Year opened: 1981 • Length: 0.85 miles	• Express buses realized travel time savings of 42% (6 minutes). • Local buses realized travel time savings of 35% (5 minutes). • Reliability of bus travel times increased for both express and local buses. • 17 months after implementation, ridership increased by 31% on local buses and by 6% on express buses. • During the peak hour period, mixed traffic speeds and total traffic volumes both increased by 10%. • As of 2002, the average speed for local buses on Madison Avenue bus lanes was only 6.5 mph. • Bus lanes and bus stops are often blocked. • Lesson learned: – Bus-only lanes may not provide sufficient travel time savings to buses in crowded downtown areas over the long term, especially if other traffic blocks the bus lanes.
16th Street • Type: Bus mall • Location: Denver, Colorado • Year opened: 1982 • Length: 1 mile	• 300-400 daily bus trips removed from downtown streets. • Granite pavers require costly maintenance. • Lesson learned: – For dedicated bus-only streets, the design must balance the appearance of the street with the functionality of the facility, since a design with a high aesthetic value may not be able to endure heavy transit use.
Nicollet Avenue • Facility statistics: • Type: Bus mall • Location: Minneapolis, Minnesota • Year opened: 1967 • Length: 11 blocks	• Bus mall improved appearance and vitality of downtown area. • Facility provides a centralized area for downtown bus service.

TABLE 2.12, continued

Spring Street • Type: Arterial contraflow bus-only lane • Location: Los Angeles, California • Year opened: 1974 • Length: 1.5 miles	• Contraflow lane increased the speed and reduced the travel time of both express and local buses. • Bus speeds increased by about 15% [13] • Movement of commuter buses to Spring Street increased bus speeds on Main Street by 16% [13] • Speeds of other vehicle traffic increased by 21% on Spring Street and by 40% on Main Street [13] • Bus routes were rerouted from parallel streets, thereby centralizing bus service.
Kalanianaole Highway • Type: Arterial contraflow HOV lane • Location: Honolulu, Hawaii • Year opened: 1975 • Length: 2.4 miles (1.9 miles contraflow, 0.5 miles concurrent flow) • Occupancy requirement: 3+	• Violation rate: 9% • Initial travel time savings of 3 minutes. • HOV lane moves 39% of total person volume in 21% of vehicles traveling on roadway. • Carpools (3+ passengers) in contraflow/concurrent flow lane averaged 45.8% less travel time and 17.8% less CO exposure than regular cars.[12] • Express buses in contraflow lane averaged 59.6% less travel time and 60.9% less CO exposure than regular cars. [12] • Non-bus HOVs (4+ passengers) in contraflow lane averaged 53.3% less travel time and 27.8% less CO exposure than regular cars. [12] • Lesson learned: – HOV lanes provide tangible health benefits in the reduction of pollutants users are exposed to.

TABLE 2.12, continued

Union Avenue • Type: Arterial reversible roadway • Location: Memphis, Tennessee • Road configuration: 4 lanes in major flow direction, 2 lanes in minor flow direction	• Roadway operated at LOS C. • Reversible lanes were a factor in 17% of accidents on roadway. • Of the accidents related to reversible lane operation, 81% were caused by drivers turning left across an adjacent lane with flow in the same direction. • Many drivers were unwilling to use the outermost reversible lane due to narrow (10 ft.) lane width and proximity to oncoming traffic. • Reversible lane configuration discontinued due to operational and safety concerns. • Lessons learned: – Reversible lanes should be sufficiently wide (12 ft. width is standard) to encourage use and minimize danger from oncoming traffic. – Left turns should be restricted to the outermost lane and to certain sections along reversible roads in order to improve safety.
Nicholasville Road (U.S. 27) • Type: Arterial reversible roadway • Location: Lexington, Kentucky • Road configuration: 3 lanes in major flow direction, 1 lane in minor flow direction, 1 two-way left-turn lane	• Traffic delays decreased and speeds increased in the major flow direction during peak periods. • Traffic delays increased in the minor flow direction during off-peak periods and the evening peak period. • Project had a benefit-cost ratio of 6.90:1. • Lesson learned: – A reversible road should have more than one lane in the minor flow direction.

TABLE 2.12, continued

Ottawa • Type: Arterial queue jumps/transit signal priority • Location: Ottawa, Ontario • Year opened: 1998 (for first queue jumps)	• Queue jumps involved implementing the following features: – Transit priority signal indication – Advanced stop bar at intersections – Bulb-outs – Lane control signals – Bus-only lanes • Bus travel times and variability in bus travel times both reduced substantially. • Use of bus-only lanes maximized. • Violation rates remained low. • No major impacts on use of GP lanes or on safety of intersections. • Lessons learned: – Buses don't always use queue jumps immediately after implementation, but use generally improves over time. – Mixed traffic doesn't always stop at the advanced stop bar, preventing buses from jumping to the front of the queue. – Moving the stop bar away from the intersection increases the length of the queue, so enough room must be provided.
Bremerton • Type: Arterial transit signal priority • Location: Bremerton, Washington	• Bus travel times reduced by 5-16%. • Possible but indeterminate impacts on cross-street traffic.
Central Expressway • Type: Arterial queue jumps • Location: Santa Clara, California • Year opened: after 1982	• Violation rates: 38% (AM), 32% (PM) • Queue jumps perform poorly despite the intersection evaluated operating at LOS F. • Poor performance is probably due to the queue jump lanes being roughly parallel to the US 101 (freeway) HOV lane. • Lesson learned: – Queue jump lanes may not perform adequately when a parallel freeway HOV lane or queue jump runs nearby.

3 IDENTIFICATION AND SELECTION OF MANAGED LANE STRATEGIES

To simplify our discussion[6], we classify strategies for managed lanes based on three factors: (1) types; (2) designs and methods of implementation; and (3) traffic management/control schemes. For example, the types of managed lanes include HOV lanes, HOT lanes, bus-only lanes, truck-only lanes, ET lanes, bus-toll lanes, truck-only toll lanes among others. A particular type of managed lanes may have a variety of designs and methods of implementation. For example, a bus-only lane can be placed on the median of a two-way arterial or as a contraflow lane on a one-way arterial. Traffic management schemes, such as transit signal priority to buses and allowing them to jump queues of waiting vehicles at intersections, can be used to further enhance the performance of managed lanes as well. In this report, we define this combination of three factors as a strategy or, more specifically, a bus-only lane strategy. Such a definition allows us to fully capture the variety or heterogeneity of managed lanes on arterials and present them in a unified framework.

Below, Section 3.1 summarizes several types of arterial managed lanes which can be potentially implemented in Florida. Section 3.2 describes their designs and methods of implementation, followed by an introduction of various traffic management schemes for managed lanes in Section 3.3. Lastly, Section 3.4 proposes a procedure for screening locations and selecting a managed lane strategy for implementation.

3.1 Types of Managed Lanes for Florida

As aforementioned in Section 2.2, we categorize types of managed lanes on arterials based on their management or control techniques such as vehicle eligibility, access control and pricing. In the literature, types of managed lanes include HOV, bus-only, HOT, ET, truck-only, bus-toll, and truck-only toll lanes. Below, we describe the specific design and implementation of HOV, bus-only, HOT, and ET lanes because these are more likely to be implemented on arterials in Florida. In principle, the bus-toll lanes are very similar to HOT lanes, and we do not treat them separately. Truck-only lanes and truck-only toll lanes have been suggested as an effective means to manage and separate (generally slower) truck traffic from other types of vehicles. However, they have not been successfully implemented in practice. When there is only one truck-only lane, trucks must enter the adjacent GP lane to pass a slow-moving truck. This would allow truck traffic to mix with other types of vehicles. Thus, there must be at least two truck-only or truck-toll lanes for this type of managed lanes to be effective. Unfortunately, truck traffic is usually too low to justify having two lanes.

3.2 Design and Implementation of Managed Lanes

Designing managed lanes involves, e.g., determining its layout, placement, length, width, and traffic separation. For each of these elements, we discuss below the available options along with their advantages and disadvantages.

---

[6] In the literature, the definition of a strategy is unclear. The discussion in Section 2 relies on the definition most common in the literature. However, such definition is cumbersome for our purpose.

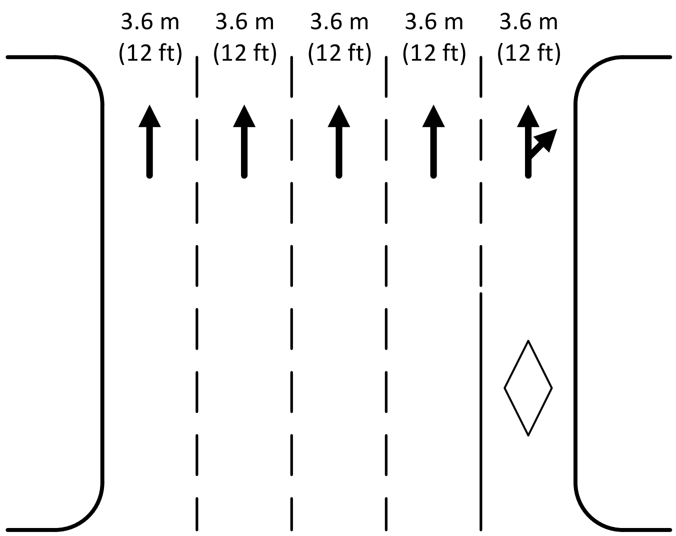
3.2.1 Layout and Placement

Managed lanes can be classified according to their placement and direction of traffic flow as (concurrent) right-side, left-side, median, reversible, right-side contraflow, and left-side contraflow.

3.2.1.1 Right-Side Managed Lanes

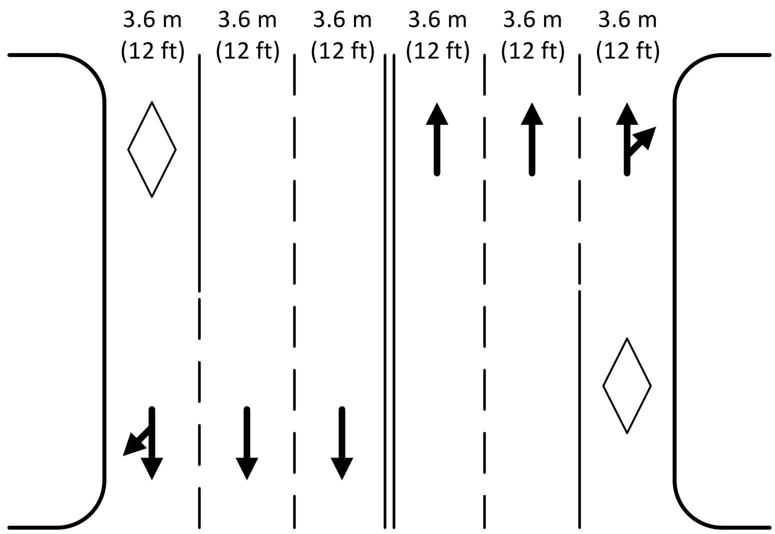
Right-side managed lanes refer to concurrent lanes located on the right side of an arterial (see FIGURE 3.1 and FIGURE **3.2**). This design has been adopted for HOT lanes in Santa Clara County, CA (see FIGURE 3.3).

The curbside lane available for parking and deliveries can be converted into a right-side managed lane. However, the issue with parking vehicles and those making deliveries must be addressed. Bus-only lanes often adopt this design because passengers can board and alight on the street side.



Source: TTI et al. (1998)

FIGURE 3.1 Right-Side Managed Lane on One-Way Street



Source: TTI et al. (1998)

FIGURE 3.2 Right-Side Managed Lane on Two-Way Street

Source: County of Santa Clara (2003)

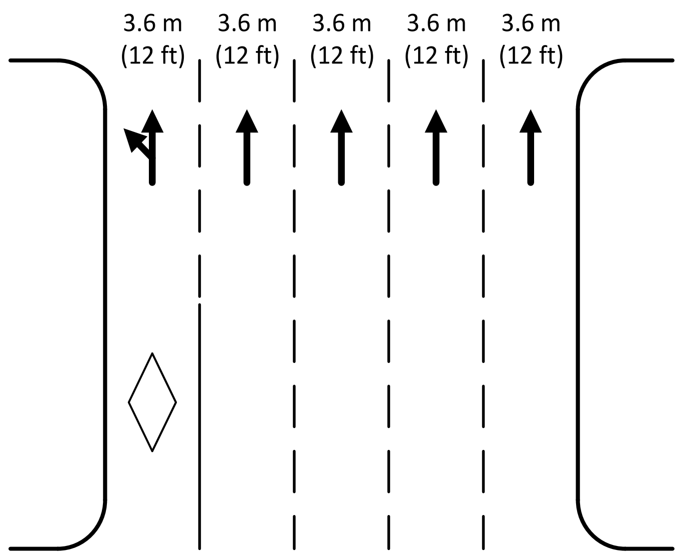
FIGURE 3.3 Right-Side Managed Lane in Santa Clara County, CA

3.2.1.2 Left-Side Managed Lanes

The left-side managed lanes (see FIGURE 3.4 and FIGURE **3.5**) refer to the concurrent lanes that are located on the left side of an arterial. Barriers can be added so that the facility operates more like a reserved lane (see FIGURE 3.6). In this case, access points must be carefully provided.

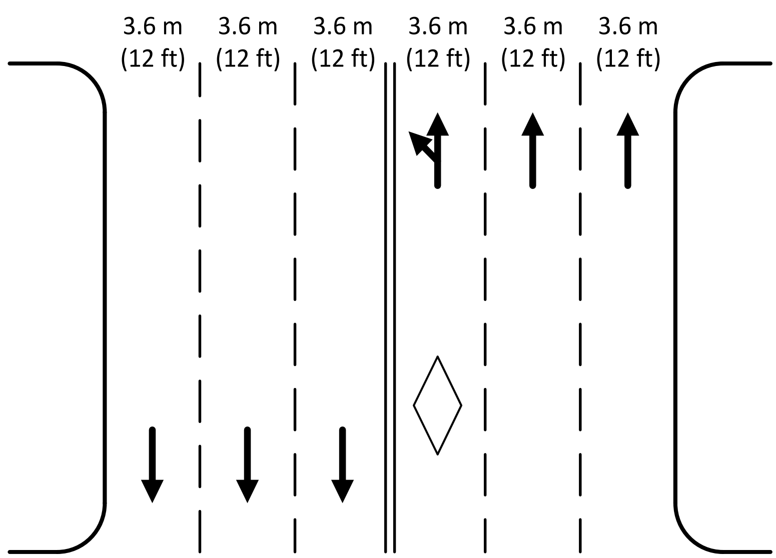
Although left-side managed lanes are less common, they offer a few advantages. First, they still allow vehicles to right-turn, park or make deliveries along curbside lanes. Second, travel speeds on left-side lanes are often higher because there is less disruption. This benefits longer-distance users. On the other hand, vehicles in left-side managed lanes (e.g., HOV lanes) need to weave into GP lanes to make right turns and it is not convenient for transit vehicles to load and unload passengers on the left-side bus-only lanes. The problem of vehicles in GP lanes making left turns needs to be addressed as well.

In general, left-side managed lanes are suitable for implementing HOV, HOT and ET lanes.



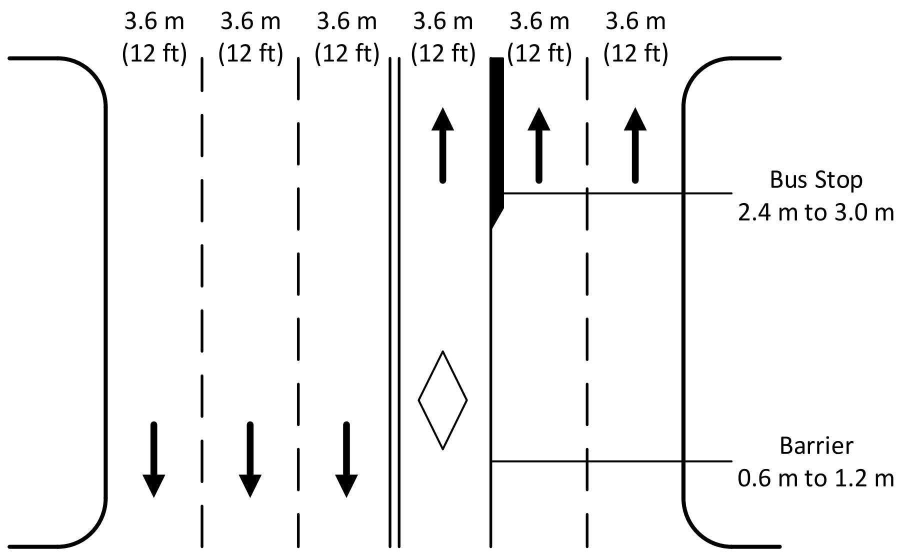
Source: TTI et al. (1998)

FIGURE 3.4 Left-Side Managed Lane on One-Way Street



Source: TTI et al. (1998)

FIGURE 3.5 Left-Side Managed Lane on Two-Way Street



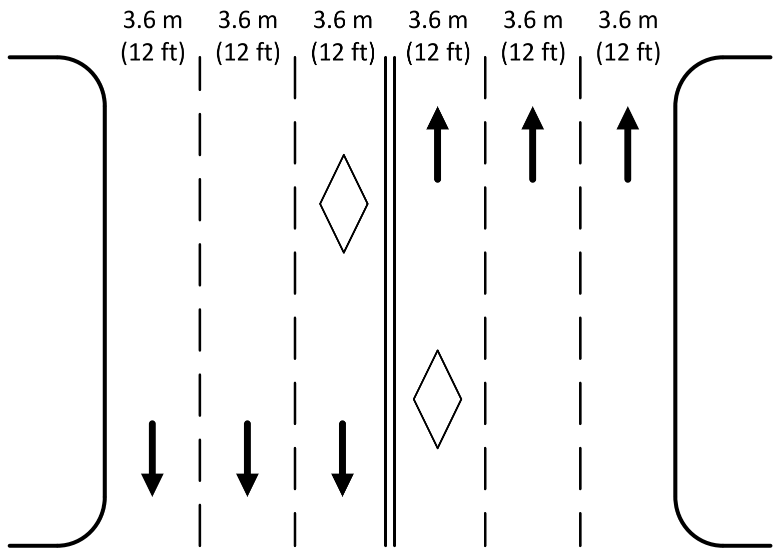
Source: TTI et al. (1998)

FIGURE 3.6 Left-Side Managed Lane with Barrier on Two-Way Street

3.2.1.3 Median Managed Lanes

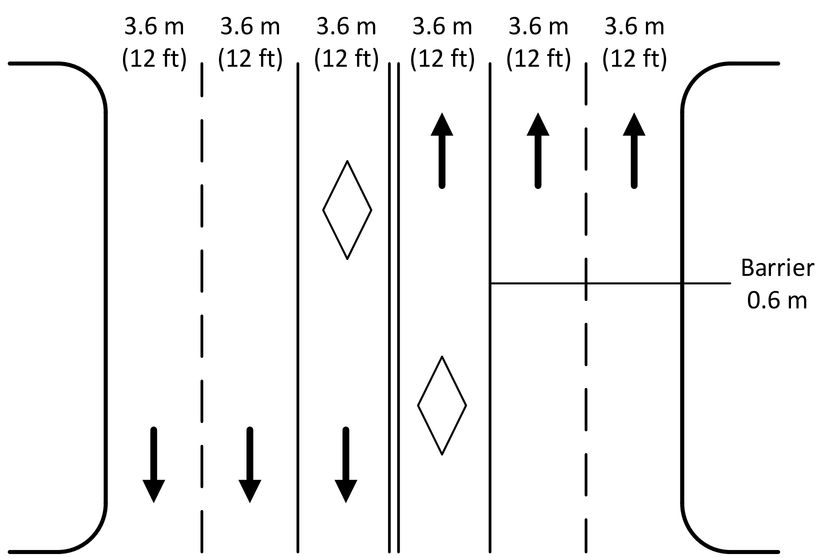
If there is a left-side managed lane in each direction of a two-way street, we refer to them as "median managed lanes". FIGURE 3.7 and FIGURE **3.8** show a sketch of a median managed lane and FIGURE 3.9 displays an actual implementation in Seoul, Korea where the managed lanes are painted in a different color (pinkish orange). It is also possible to physically separate median managed lanes from others using, e.g., concrete barriers.

The advantages and disadvantages of median managed lanes are similar to left-side managed lanes because the former consists of left-side managed lanes in each direction. Median managed lanes are suitable for implementing HOV, HOT and ET lanes.



Source: TTI et al. (1998)

FIGURE 3.7 Median Managed Lane



Source: TTI et al. (1998)

FIGURE 3.8 Median Managed Lane with Barrier

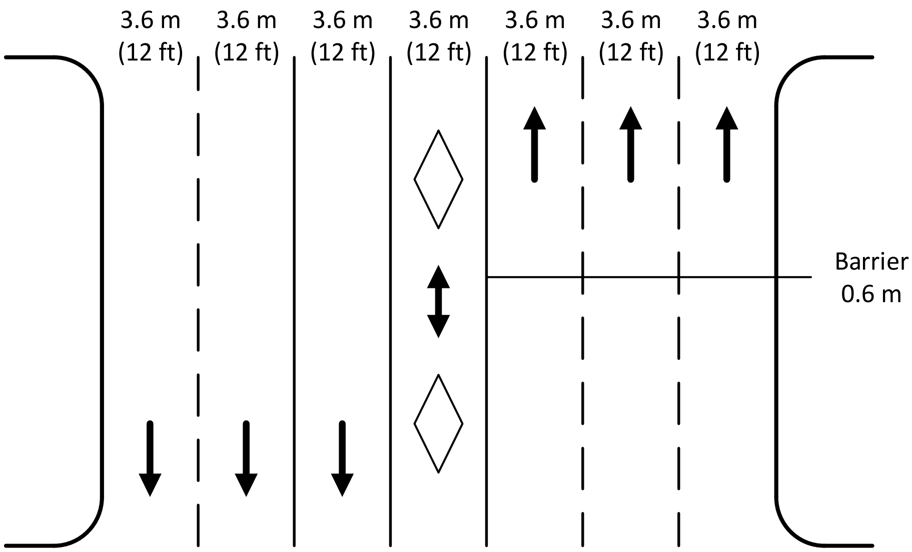
FIGURE 3.9 Median Managed Lane in Seoul, Korea[7]

3.2.1.4 Reversible Managed Lanes

Traffic in a reversible managed lane (see FIGURE 3.10) can be in either direction at different times. This design is particularly applicable to corridors where traffic demand presents a "tidal" phenomenon. The design allows traffic authorities to manage traffic under unusual circumstances such as construction, particularly on bridges and in tunnels. FIGURE 3.11 displays a reversible managed lane on Lions Gate Bridge in Stanley Park, Vancouver.

This design can make good use of all lanes and leave curbside lanes available for parking, delivery, and turning right. It is suitable for implementing all types of managed lanes. However, it may be inconvenient for vehicles in GP lanes to make a left turn when there is a managed lane in the median. This issue needs to be addressed.

[7] Source: http://www.traffictechnologytoday.com/news.php?NewsID=3849



Source: TTI et al. (1998)

FIGURE 3.10 Reversible Managed Lane

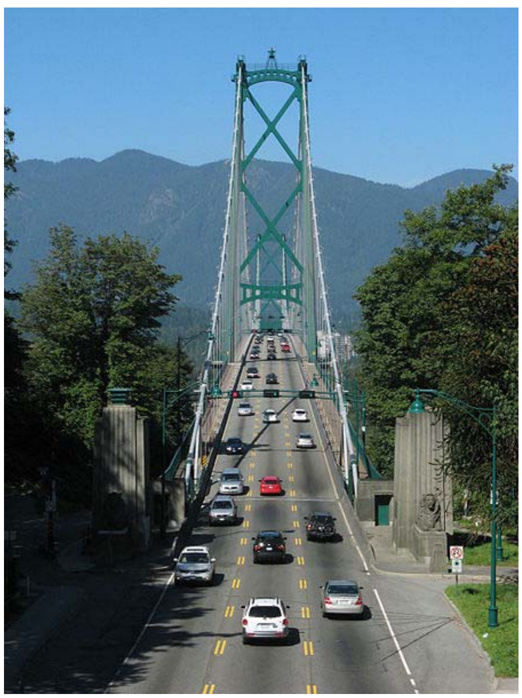


FIGURE 3.11 Reversible Managed Lane on Lions Gate Bridge, Stanley Park, Vancouver[8]

3.2.1.5 Right-Side Contraflow Managed Lanes

A right-side contraflow managed lane (see FIGURE 3.12 and FIGURE **3.13**) is on the right side of the street when traveling in the direction of the lane. When implemented, the arterial must have sufficient capacity such that the GP lanes are not be negatively impacted by the lane. See FIGURE 3.14 for a right-side contraflow bus-only lane in San Juan, Puerto Rico.

[8] Source: http://en.wikipedia.org/wiki/File:Lions_Gate.jpg

Such a design takes advantage of the capacity often available in the non-peak direction. However, the design is normally limited to bus-only lanes, since regular drivers are not accustom to driving on them (AASHTO, 2004).

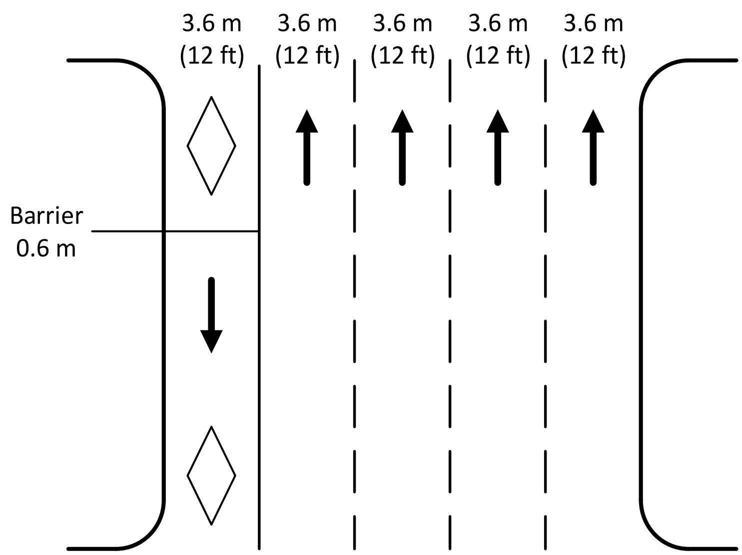


FIGURE 3.12 Right-Side Contraflow Managed Lane on One-Way Street

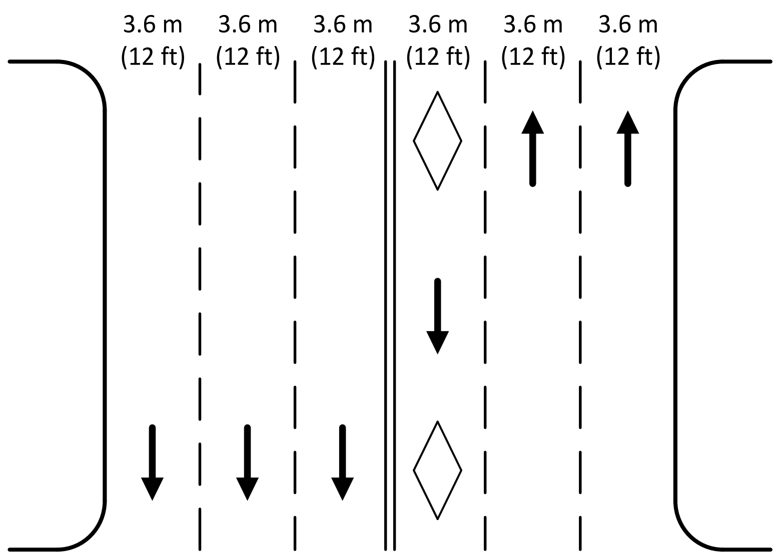


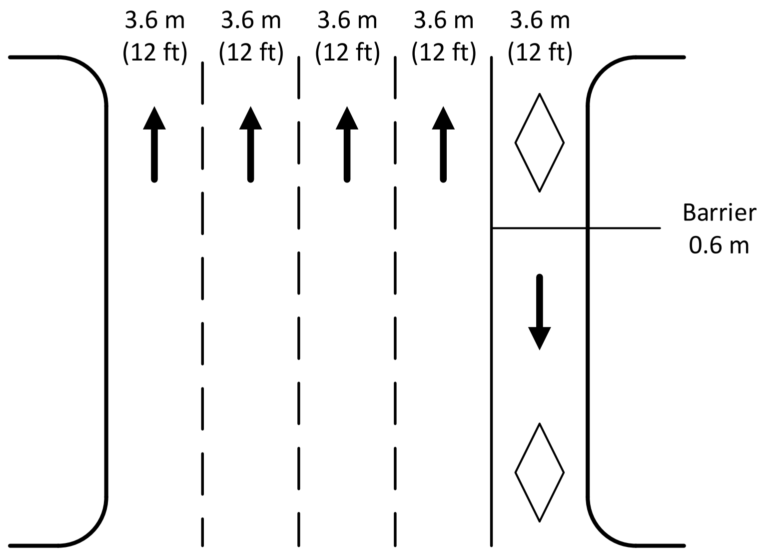
FIGURE 3.13 Right-Side Contraflow Managed Lane on Two-Way Street

FIGURE 3.14 Right-Side Contraflow Bus-Only Lane in San Juan, Puerto Rico

3.2.1.6 Left-Side Contraflow Managed Lanes

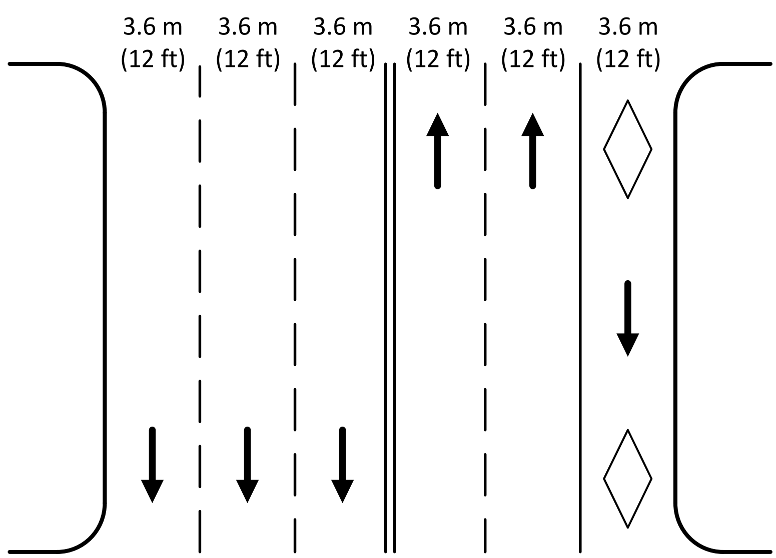
A left-side contraflow managed lane (see FIGURE 3.15 and FIGURE **3.16**) is located near the curb, which is on the left side of the street when traveling in the direction of the lane.

The advantages and disadvantages of such a design are similar to those of right-side contraflow managed lanes. The design is normally used for bus-only lanes, but is less popular on streets with many bus stops, because additional space is needed to build bus stops on the right side of the bus-only lane.



Reproduced by authors based on TTI et al. (1998)

FIGURE 3.15 Left-Side Contraflow Managed Lane on One-Way Street



Reproduced by authors based on TTI et al. (1998)

FIGURE 3.16 Left-Side Contraflow Managed Lane on Two-Way Street

3.2.1.7 Summary and Recommendation

TABLE 3.1 summarizes the advantages and disadvantages of different layouts presented above. The choice of layouts depends on many factors such as the number of lanes and turning movements, tidal traffic condition, and the duration and extent of congestion.

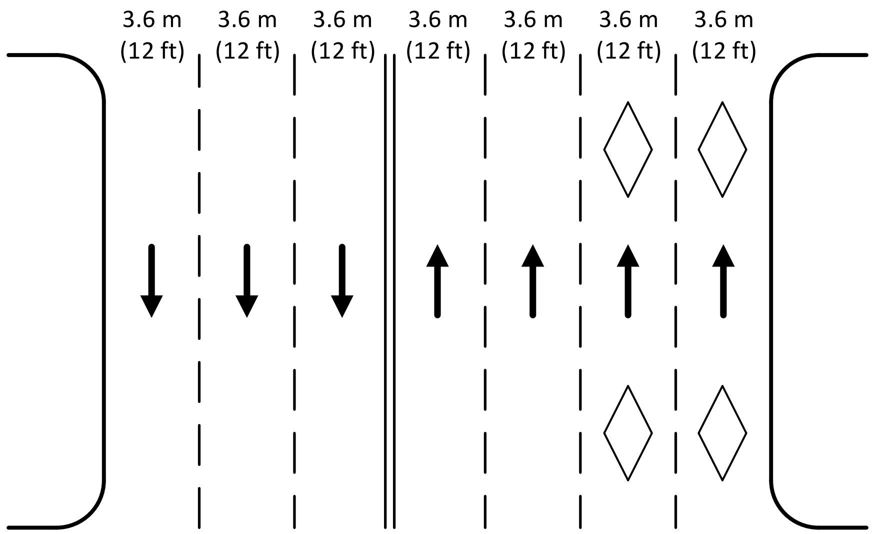
TABLE 3.1 Pros and Cons of Different Layout Designs

Layout	Pros	Cons
Right-side	Easy to implement	Parking and deliveries need to be addressed
Left-side	Offer higher speed and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Median	Offer higher speed and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Reversible	Make use of capacity in the non-peak direction and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Right-side contraflow	Make use of capacity in the non-peak direction	Usually limited to bus-only lanes
Left-side contraflow	Make use of capacity in the non-peak direction	Usually limited to bus-only lanes and need to address the bus stop issue

If local buses are allowed to load and unload passengers in HOV or HOT lanes, there should be more than one such lanes (see FIGURE 3.17). When possible, a median next to the managed lane can be used (see FIGURE 3.18).

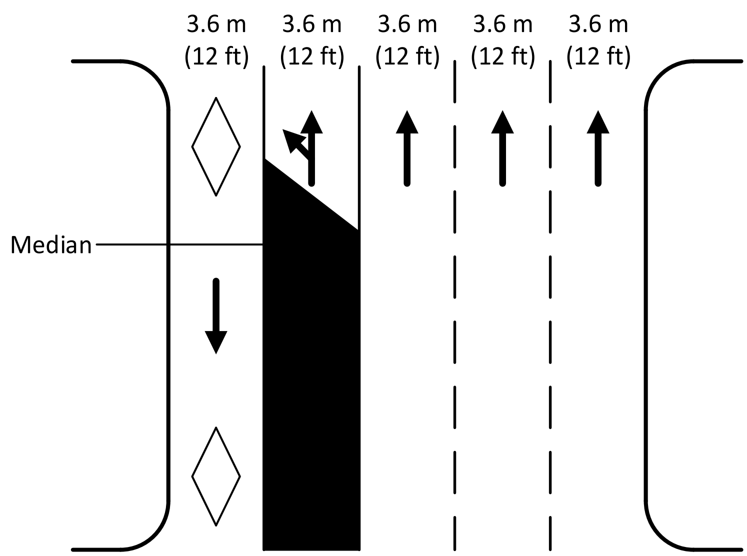
For bus-only lanes, well-located bus stops can (a) improve the safety and convenience of passengers, (b) reduce the conflicts between local buses and regular vehicles, and (c) avoid generating traffic bottlenecks. Detailed design guidelines for bus stops can be found in TTI (1996).

HOV lanes that are underutilized are often converted into HOT and ET lanes. The public also seems to accept such conversion more easily than converting a GP lane into some form of managed lanes. Similarly, there is a similar public support for converting parking or turning lanes into managed lanes.



Reproduced by authors based on TTI et al. (1998)

FIGURE 3.17 Multiple Right-Side Managed Lanes on Two-Way Street



Reproduced by authors based on TTI et al. (1998)

FIGURE 3.18 Right-Side Contraflow Managed Lane with Median on One-Way Street

3.2.2 Lane Length and Width

The length of a managed lane can range from one to several blocks depending on its purpose. Managed lanes for express buses or HOVs are typically longer. The length of a bus-only lane depends on the configuration of bus routes. HOT or ET lanes, either as a lane in a long arterial or a bridge or tunnel bypassing a congested bottleneck, must offer adequate travel time savings to justify paying tolls (Dragan, 2013).

When there are active pedestrian movements, the width of a curbside managed lane should be 4.0 to 4.3 meters. Otherwise, the width of these lanes is typically 3.6 meters, definitely not less than 3.3 meters. Further, if there are barrier separations, the lane should be 0.6 to 1.2

meters wider according to the characteristics of the barriers to be discussed below (AASHTO, 2004).

3.2.3 Lane Separations

There are three primary types of lane separation: striping; buffer separation using plastic tubes; and concrete barriers.

Striping costs the least and is easy to implement and maintain. TABLE 3.2 summarizes the types of striping used for different managed lanes. In general, the lack of physical barriers encourages violations and illegal weaving that can create safety issues or prevent a managed lane facility from achieving its operational objectives.

TABLE 3.2 Striping Used in Different Types of Managed Lanes

Type of Managed Lane	Type of Striping
Concurrent	Solid white lines
Contraflow	Solid double lines
Median	Solid double yellow lines
Reversible (24-hour operation)	Solid double yellow lines
Reversible (Less-than-24-hour operation)	Skip double yellow lines

Source: AASHTO (2004)

Plastic tubes are tubular markers, pylons, or stanchions that offer a buffer-separation option for managed lanes. They can be from 20 inches to 3 ft. tall, and mounted permanently to the pavement or attached to the roadway with adhesive. The recommended spacing between pylons is 20 feet (Charles, 1990). However, vehicles traveling at a low speed (e.g., 30 mph) may be able to weave between pylons. In this case, pylons should be placed in a smaller spacing than 20 ft. (Kuchangi et al., 2013). Pylons have been used on several HOT lanes on freeways, e.g., I-95, SR-91, and I-10.

FIGURE 3.19 shows the buffer separation on 95 Express, Florida. Such separation requires less right-of-way and costs less than concrete barriers. Further, it does not restrict the access of emergency and police vehicles, as those vehicles are allowed to weave between pylons. However, pylons are prone to damage during operations and need replacement, which increases maintenance costs.

Concrete barriers (see FIGURE 3.20), on the other hand, have high initial cost, require more right-of-way, and limit the access of emergency and police vehicles (Poole and Orski, 1999). However, they eliminate unlawful ingress and egress and help in maintaining safe traffic operations when high speed differentials exist between managed and GP lanes. With concrete barriers, there is less mental stress on drivers of HOVs knowing that those on an adjacent GP lane cannot weave into the managed lanes (Kuchangi et al., 2013).

TABLE 3.3 summarizes the advantages and disadvantages of all separation types. Along with factors such as enforcement strategies, speed differentials and traffic dynamics, the available resource and right-of-way generally dictate the selection of the separation type.

FIGURE 3.19 Buffer Separation on 95 Express, Florida[9]

FIGURE 3.20 Concrete Barriers on I-15 Express Lanes, San Diego, California[10]

[9] Source: http://www.itsinternational.com/sections/nafta/features/floridas-high-occupancy-tolling-success-in-reducing-congestion/

[10] Source: http://ops.fhwa.dot.gov/freewaymgmt/publications/frwy_mgmt_handbook/revision/jan2011/mgdlaneschp8/sec8.htm

TABLE 3.3 Summary of Separation Types

Separation Types	Advantages	Disadvantages
Pavement Markings	Cheapest to implement; very low maintenance cost; unconstrained access of emergency and police vehicles	Higher number of violations; safety and operational concerns
Plastic Pylons	Require less right-of-way; less installation cost than concrete barriers; easier enforcement than striping; easy access for emergency vehicles	More expensive than striping; higher maintenance cost
Concrete Barriers	Eliminate unlawful weaving; improve safety; reduce mental stress of drivers	Very high construction cost; limit the access of emergency and police vehicles; wider buffer area

3.2.4 Signs and Markings

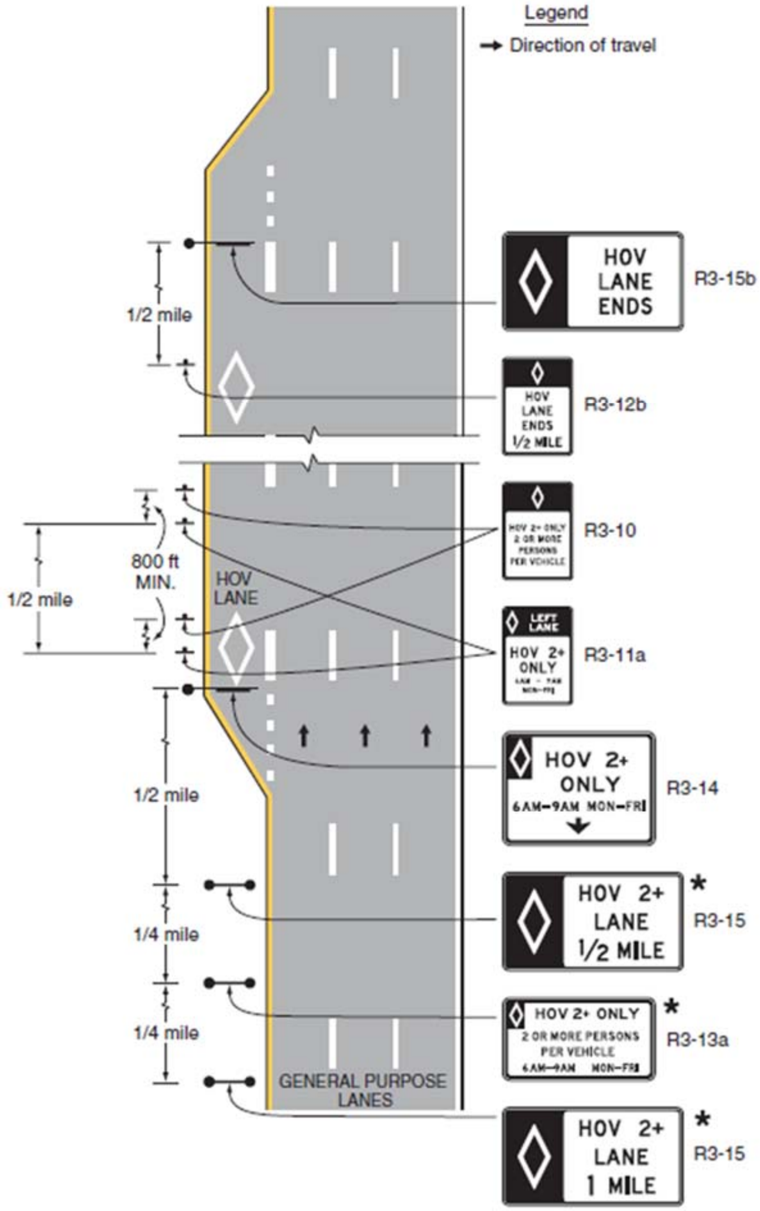
Signs and markings are necessary for the operations of managed lanes. Their design and implementation should follow the Manual of Urban Traffic Control Devices (MUTCD) (FHWA, 2009).

According to MUTCD, managed lane regulatory signs mainly include those that specify the minimum number of occupants, display periods of operation, and designate the beginning and end of managed lanes. The symbol and word message displayed on the signs should depend on the type of managed lanes, such as HOV or bus-only lanes (see FIGURE 3.21). Changeable message signs can supplement static signs. However, they should be place sufficiently far ahead of the entrance to the HOT or ET lanes to announce toll rates dynamically and allow drivers to make a decision whether to pay and use the lanes. Such signs can be placed overhead in a certain distance before each entrance. The distance and configuration of the signs may vary across facilities and depend on the operating speed, driver familiarity, and other factors. More detailed information about the size, placement and design of managed lane signs can be found in Chapter 2G of MUTCD. FIGURE 3.22 shows the placement of the signs on HOV lanes.

Markings should be painted in applicable pavement, including symbols and additional wording (see FIGURE 3.23). As stated in MUTCD, markings should be spaced as close as 80 ft. on city streets. More detailed of managed lane markings design can be found in Chapter 3D of MUTCD. In particularly, maintenance activities need to be scheduled for markings, especially in the areas of high traffic volume or with humid weather.

Source: FHWA (2009)

FIGURE 3.21 Examples of HOV Signs



Source: FHWA (2009)

FIGURE 3.22 Example of Signs on HOV Lane

FIGURE 3.23 Example of Markings on Managed Lane[11]

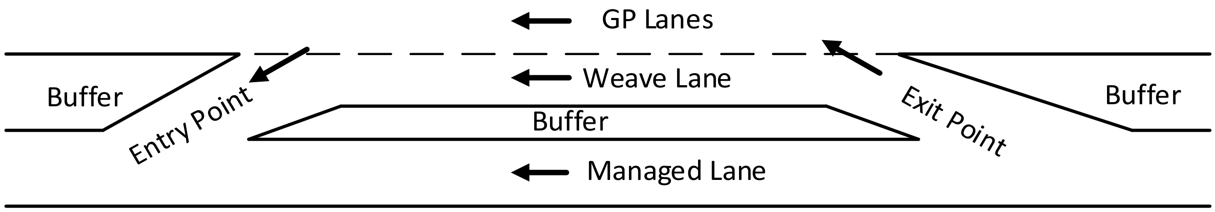
3.2.5 Access Points

The design of access points will largely depend on the type, layout, and placement of a managed lane, and the means of separation. For contraflow managed lanes, the access points usually begin and end at intersections, so that eligible vehicles can only enter or exit the lanes at intersections for the apparent safety reason. For (concurrent) managed lanes with continuous access, eligible vehicles can enter or leave the lanes at any point. Such design is often used for bus-only and HOV lanes. For buffer- or barrier-separated managed lanes, most of which are HOT or ET lanes, vehicles can only enter/exit at ingress/egress points. Since weavings associated with ingress or egress may cause safety issues and interrupt traffic flow, the number of access points should be limited. On the other hand, frequent access points provide convenience to drivers and attract more traffic demand. It is a tradeoff that planners and decision makers have to make.

Usually, access points are provided by only suspending physical separation or changing prohibitive lane change striping to permitted striping, e.g., a single broken line. Sometimes, a weave lane is added to better maintain speed and flow in the managed lane (see FIGURE 3.24). The design of access points for freeway managed lanes has been discussed in various reports. In WSDOT (2006), it is suggested that "if a minimal lane shift distance of 500 feet is used to locate the access point and if access to or from the HOT/HOV lane is restricted to one movement, then the access opening could be as short as 500 feet… A combined access (allowing both ingress and egress) using the same minimal lane change distance should provide at least 1000 feet (2 × 500 feet per lane change) of access." However, for arterial managed lanes, the access point length can

[11] Source: http://en.wikipedia.org/wiki/File:Newark_Penn_Station_XBL_%28exclusive_bus_lane%29.JPG

be shorter due to lower speeds. Particularly, if an access point is located near an intersection, the space of the intersection can be utilized to make the access point length even shorter.



Reproduced by authors based on WSDOT (2006)

FIGURE 3.24 Example of Weave Lane Used for Access Points Design

3.2.6 Pedestrian and Bicycle Conflicts

If managed lanes are newly added, the pedestrian conflicts need to be considered carefully. The added lanes will increase the walking time and thus negatively affect the safety of pedestrians. To resolve the issue, mid-street refuge islands can be provided as well as pedestrian skywalks or tunnels. Alternatively, the walking phase of signal control can be made longer and the vehicle speed limit set to be lower. For contraflow or reversible managed lanes, additional signs should be provided to notify pedestrians the contraflow vehicles.

For curb-side concurrent managed lanes, if the volume of bicycle flow is high, bicycle conflicts should be taken into account as well. To reduce the conflicts, one bicycle lane can be added next to the managed lane (see FIGURE 3.25) or the lane can be widened by 0.6 to 1.2 m to accommodate bicycles (see FIGURE 3.26). However, for the contraflow curb-side managed lanes, bicycles should be restricted to ensure safety and an efficient operation of the contraflow managed lanes.

FIGURE 3.25 Example of Managed Lane with Separate Bicycle Lane[12]

[12] Source: http://citytransport.info/Digi/3952a.jpg

FIGURE 3.26 Example of Managed Lane Accommodating Bicycles[13]

3.2.7 Intersection Enhancement

If intersections are oversaturated, intersection enhancement can be carried out, such as constructing modern roundabouts, particularly, overpass and underpasses (see FIGURE 2.14 and FIGURE **2.15**) to increase intersection capacity and help managed lanes operate fluidly. Such enhancements are certainly costly to implement. For a generic underpass, the cost is estimated to be $41.8 million. However, the toll revenue generated from the underpass (or overpass) can be used to pay for its construction cost (Swenson and Poole, 2012). A criterion for deciding whether to implement an overpass or underpass in Swenson and Poole (2012) indicates that, if the queue at an intersection is shorter than one-fourth mile, there is no much benefit to build an overpass or underpass. In the same publication, the authors also state that the capacity increased by an intersection overpass or underpass is significantly higher than that offered by adding new lanes along the whole corridor.

3.3 Traffic Management Schemes

Various traffic management schemes can be used to enhance the performance of managed lanes on arterials. There are three categories of traffic management schemes: intersection treatment, segment management and enforcement. An intersection treatment allows vehicles in managed lanes to pass through intersections without significant delay. Common objectives in segment management are to manage traffic demand and improve the throughputs of managed lanes between intersections. In general, enforcement ensures that rules and regulations

[13] Source: http://www.patchwayjournal.co.uk/2012/06/15/highwood-road-petition-falls-deaf-ears-south-glos-council/

of managed lanes (e.g., vehicle eligibility) are followed. Below, we describe these categories of management schemes in detail.

3.3.1 Intersection Treatment

3.3.1.1 Queue Jump

A queue jump provides the priority of passage to vehicles on managed lanes at intersections. An example is shown in FIGURE 3.27 where one additional lane is provided for local buses to bypass the queue at the intersection. Usually, a special signal phase is designated to the queue jump to allow eligible vehicles to cross the intersection before other vehicles. With queue jumps, eligible vehicles can reduce delay at signalized intersections and improve their on-time performances. Mainly, there are three ways to design and implement a queue jump.

FIGURE 3.27 Queue Jump[14]

3.3.1.2 Queue jump with a continued lane

FIGURE 3.28 is a sketch of a queue jump with a continued lane for buses. The design helps buses cut to the front of the queue. Also, buses do not need to change lanes to load or unload passengers if there is a far-side bus stop. Therefore, bus delay at the intersection can be reduced and travel time reliability may thus be enhanced.

However, right-turn movements of the vehicles on GP lanes are affected negatively. Therefore, if the right-turn traffic volume is high, this type of treatment is not recommended. On the other hand, it may take some time for buses or other eligible vehicles to merge into the GP

[14] Source: http://www.metrojacksonville.com/article/2007-jan-brt-better-quality-but-not-rapid-transit#.VGTI0ckhC7g

lanes during peak hours. In this case, early green can be provided to ensure buses to jump the queue. This queue jump with early green is similar to the next type of queue jump below.

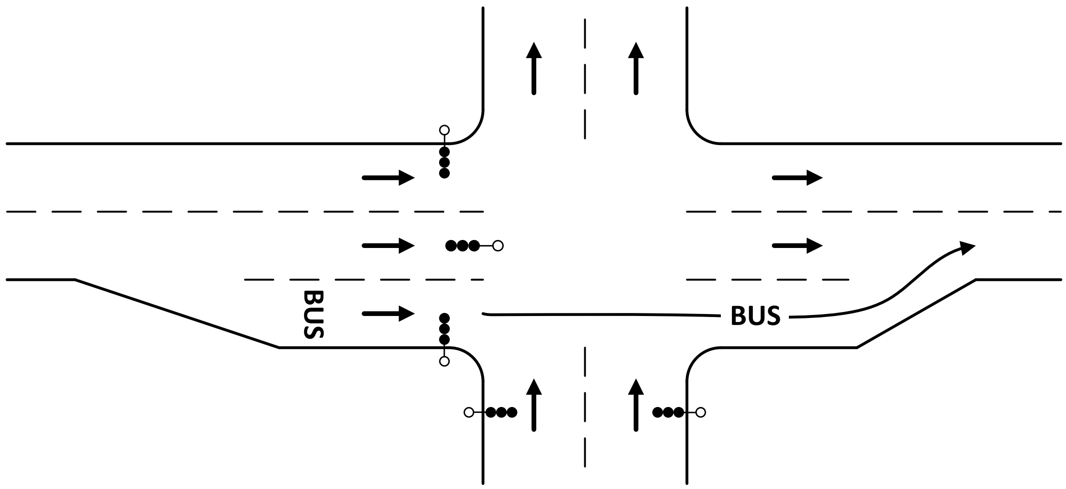


FIGURE 3.28 Queue Jump Continued Lane

3.3.1.3 Queue jump lane with designated signal

A queue jump lane coupled with a designated signal helps eligible vehicles bypass the queue on GP lanes, as shown in FIGURE 3.29. The signal provides an early green of a few seconds to give the vehicles in the queue jump a head start. Similar to a queue jump with a continued lane, this type of queue jump does hinder the right turns of vehicles on GP lanes.

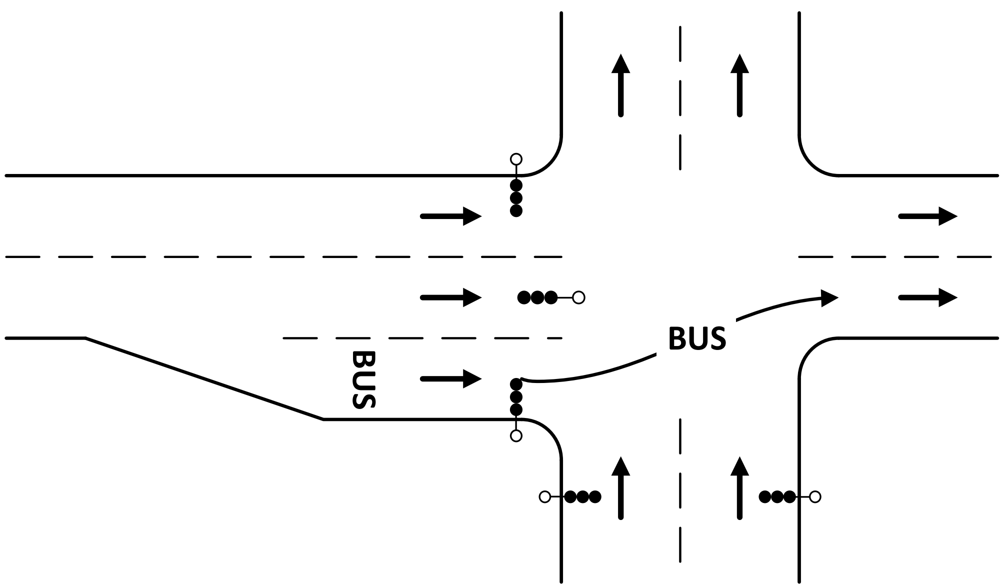
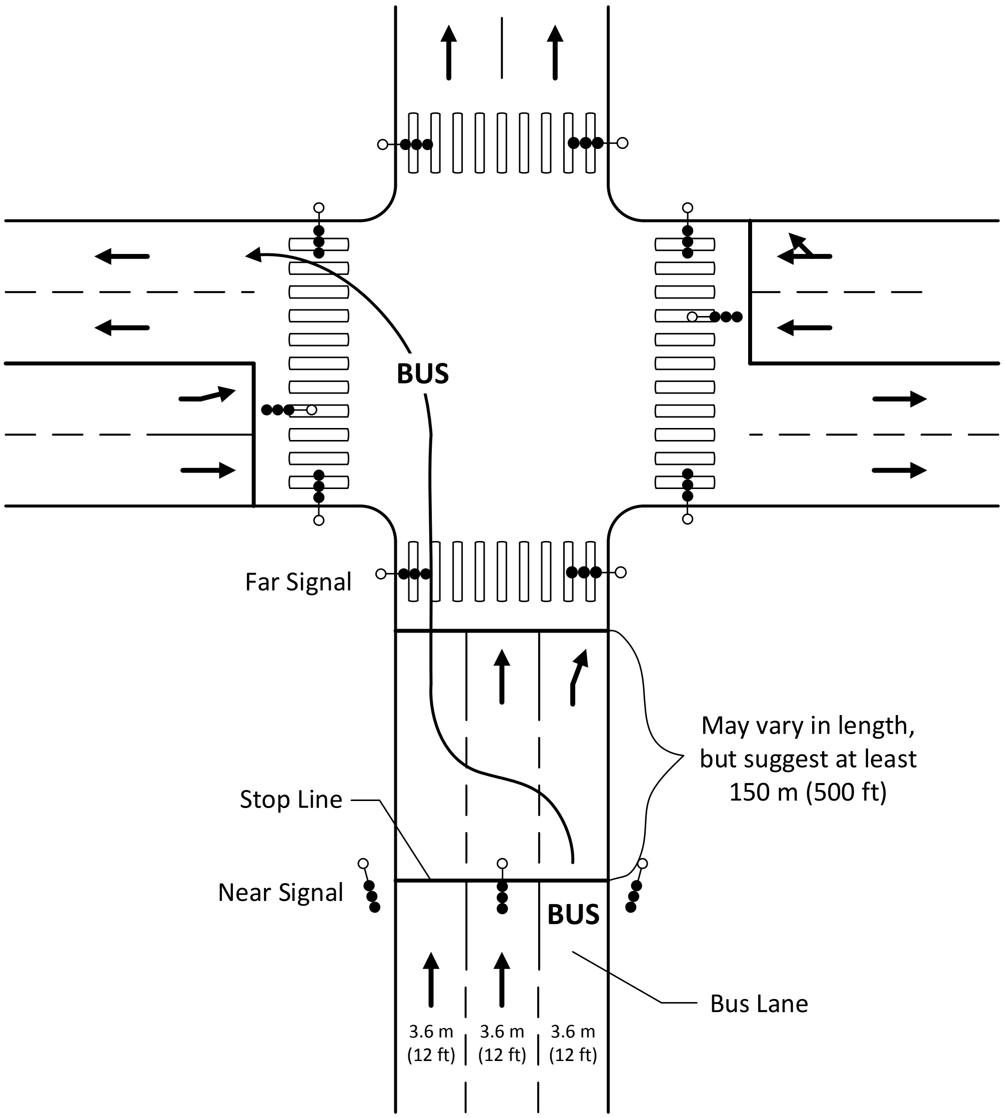


FIGURE 3.29 Queue Jump Lane with Designated Signal

3.3.1.4 Queue jump with bus advance area

A bus advance area, as illustrated in FIGURE 3.30, is an effective way to provide buses with a head start when turning left. In the figure, the near signal stops GP vehicles at the stop line, while buses can bypass them and proceed to the main signal. A few seconds later, when the far signal turns green, the near signal releases the GP vehicles, so that they join the queue behind the buses. This treatment, however, requires space to store queues, and thus may not be practical in dense urban streets where intersections are close to each other.



Source: TTI (1998)

FIGURE 3.30 Queue Jump with Bus Advance Area

3.3.1.5 Signal Control

Coupled with managed lanes, signal control can offer eligible vehicles additional preferential treatment. Similar to the queue jumps, these schemes reduce delay at signalized intersections and improve travel time reliability for eligible vehicles.

Signal timing can be adjusted to favor the approach, in which managed lanes are present. Below is a summary of possible adjustments:

- A coordination signals along the direction of managed lanes can decrease the number of stops and total delay for vehicles traveling on the managed lanes.
- Designating a phase to managed lanes at certain intersections may further reduce delay for eligible vehicles.
- For fixed control, increasing the green split of the managed lane approach leads to a reduction of passenger delay rather than vehicle delay.
- For actuated control, providing more green extension and larger maximum green time allows more eligible vehicles to clear an intersection.

The above adjustments can be made for HOV, HOT or ET lanes. However, they may not be feasible at saturated or oversaturated intersections. The key is to ensure that the adjustments do not substantially increase the delays for vehicles on GP lanes. Otherwise, the adjustments may raise public acceptance issues.

Signal priority offers vehicles on managed lanes a preferential treatment and allow them to pass through signalized intersections more smoothly. As aforementioned, it can be used in conjunction with a queue jump. Often, it is also offered to in-service buses.

Transit signal priority has been identified as a critical technology for deployment of BRT systems and for improvement of traditional transit services. Deployments of transit signal priority have occurred in many cities across the country such as Chicago, Portland, Charlotte, Seattle and Los Angeles. Most of these systems provide early green or green extension to accommodate the passing of a bus at a signalized intersection without considering the resulting disruption to otherwise well-coordinated signaling system across the street network. A "point" detection means is employed to detect the approaching buses at a fixed location or within a limited area. It provides a "short notice" to the traffic signal control system and would result in late calls that have limited lead time to borrow "seconds" from the remaining phases for early green treatment or could miss the potential green extension treatment.

In contrast, an adaptive transit priority system provides priority to transit vehicles while trying to minimize negative impacts to the minor-phase traffic. The system would have a continuous detection means, such as GPS, to sense the approaching bus continuously so that the bus arrival time can be predicted and updated in a real-time manner. With the predicted bus arrival information, the system can determine a real-time signal timing strategy to accommodate the bus arrival while explicitly considering the impacts on the non-transit vehicles and ensuring pedestrian safety. The timing strategy should make a trade-off between transit delay and traffic delay and be adaptive to the movement of the transit vehicle and the prevailing traffic condition (Zhou et al, 2004).

3.3.1.6 Turning Movement Management

Regulating turning movements is critical for ensuring the success of arterial managed lanes. Right-turn vehicles crossing a right-side managed lane (see FIGURE 3.1) and left turns crossing a left-side (see FIGURE 3.4) or median managed lane (see FIGURE 3.7) interfere with the operations of managed lanes. These types of turning movements of vehicles on GP lanes should be prohibited or limited to ensure the travel time reliability of managed lanes on arterials.

At the intersections where turning movements are allowed and severe interference arises, turn bays can be added to reduce the interference. In this case, all the turns can only be attempted in the turn bays. Vehicles on GP lanes have to merge into the managed lanes and then weave into the bays if they want to make a turn.

3.3.1.7 Signal Controlled Roundabout Treatment

The first roundabout with signal control was designed in the United Kingdom in 1959. However, it was only in the early 1990s that signal controlled roundabouts started to become more common (Ridding and Phull, 2009). Traffic signals installed at the roundabout (see FIGURE 3.31) are able to regulate the traffic flows entering the roundabout and their speed. Doing so (a) can help the roundabout operate more fluidly, (b) balance and improve the capacity, (c) reduce the delay and accident, and (d) improve safety (Department for Transport U.K., 2009). This type of treatment is usually used during peak hours when the number of vehicles entering a roundabout exceeds its capacity. When there is ample space, queue jump and signal control can also be used with this type of roundabouts.

Source: Department for Transport U.K. (2009)

FIGURE 3.31 Signal-Controlled Roundabout

3.3.2 Segment Management

3.3.2.1 Pricing Strategies

HOT and ET lanes rely on pricing to maintain superior traffic conditions. Successful operations of these lanes are mainly affected by employing an effective pricing strategy. Pricing can be either time-of-day or dynamic. In dynamic pricing, the toll price varies with the real-time traffic conditions and it is typically updated every few minutes. On the other hand, tolls that vary with time-of-day are predetermined and based on a toll schedule developed from historic traffic data. Time-of-day tolling is useful for facilities that have a stable traffic demand pattern. Between these two types of tolling, data from real-world implementations of HOT and ET lanes on freeways have demonstrated that dynamic tolling is more effective at achieving the operating objectives of HOT and ET lanes. For both types of pricing, many agencies also establish the lowest and highest toll price. When setting these two prices, drivers' willingness-to-pay and public acceptance must be considered.

A HOT or ET lane facility can be single-segment or multi-segment. For the former, there is typically an entrance at the start of the segment with a tolling facility and an exit where the segment ends. Motorists who enter the facility during the same tolling interval pay the same toll amount. Pricing of a single-segment facility has been well studied by, e.g., Yin and Lou (2009) and Lou et al. (2011).

A HOT or ET lane consisting of multiple segments has several entrances and exits that are located at some distance from each other. Compared to single-segment, a multi-segment facility is more challenging to price. In principle, pricing should provide superior traffic flow conditions on the HOT or ET lanes while maximizing roadway's throughput. Moreover, it should avoid creating inequality issues among motorists entering the facility at different ingress points. It also need to ensure similar traffic conditions within every segment of the facility without causing excessive lane changes before each HOT or ET lane entrance. Although a multi-segment facility often has multiple tolling points, a motorist does not necessarily have to pay at each point. Where a motorist is charged depends on the toll structure implemented. In general, the toll structures for multi-segment facilities can be classified as zone-based, origin-specific, OD-based, and distance-based. All four structures have been implemented in practice on freeways.

Below are descriptions for each toll structure along with their advantages and disadvantages. Each description addresses a multi-segment HOT-lane facility illustrated in FIGURE 3.32. In this facility, there are two HOT lanes and three GP lanes. The HOT lanes are separated from the GP lanes by double solid line. Motorists can enter and exit the HOT facility only at the access points indicated by dashed lines. In the figure, I1, I2, and I3 denote the entrances and O1, O2, and O3 designate the exits to and from the HOT lanes, respectively. A toll gantry is generally located downstream from each entrance.

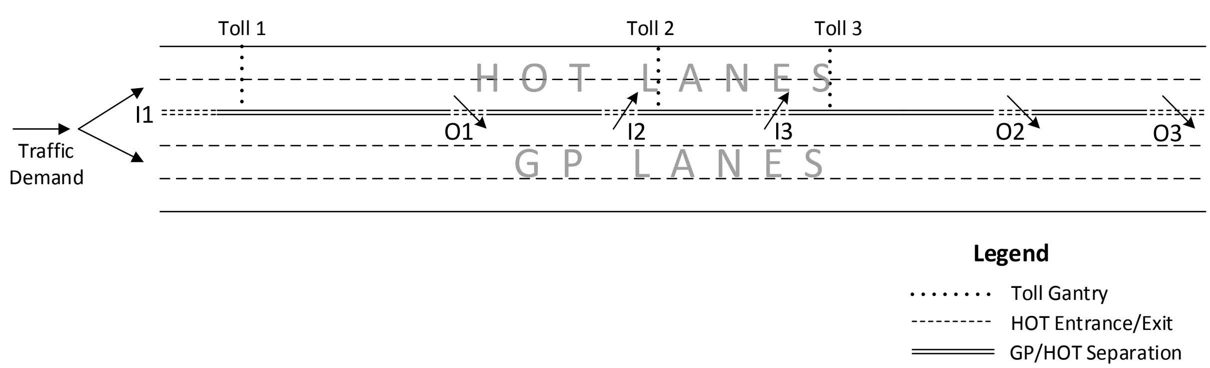


FIGURE 3.32 Example of a Multi-Segment HOT Lane

- In zone-based toll structure, a HOT lane facility is divided into multiple zones. Whenever a motorist enters a new zone, he or she pays a specific toll. Consequently, the toll amount that a motorist pays depends on the numbers of zones he or she has traversed. Each zone can include multiple HOT lane entrances and exits. The toll amount for a zone is computed at the first entrance to a zone and will be assigned to all the entrances that belong to the same zone. When dynamic pricing is implemented, the toll calculation algorithm for a zone should consider the traffic conditions in the entire zone and, in some cases, the traffic conditions in the downstream zones as well. The toll at all the entrances that belong to the same zone is the same, however. A vehicle traveling on a zone-based HOT lane has to make a lane-choice decision every time it enters a new zone. For instance, suppose that the facility in FIGURE 3.32 is divided into two zones, one from I1 to O1 and the other from I2 to O3. In this case, Zone 1 has one entrance and one exit. Let "Toll 1" denote the toll for Zone 1. As shown in FIGURE 3.32, Zone 2 has two entrances (I2 and I3) and two exits (O2 and O3). Let "Toll 2" denote the toll for Zone 2. Motorists traveling through Zone 1 will pay toll 1 and motorists traveling through the entire facility will pay Toll 1 plus Toll 2. Travelers entering the facility at either I2 or I3 and exiting at either O2 or O3 pay the same toll, i.e., Toll 2.

The zone-based toll structure has been implemented on the I-15 Express lanes in Salt Lake City, the I-10 HOT lane corridor in Houston, and the MnPass I-394 HOT lanes in Minneapolis (see FIGURE 2.3).

- In the origin-specific structure, the toll amount a motorist will pay depends only on where he or she enters the facility. More precisely, a traveler pays the toll amount that is displayed on a sign at his or her entry point regardless of how far the traveler is going to travel on the HOT lanes. Consequently, the traveler will only have to face the lane choice once. In the example network in FIGURE 3.32, there are three origins, I1, I2, and I3. Motorists who enter at I1 will pay toll 1 regardless of which exit, O1, O2, or O3, they are going to take. In this case, a driver who travels from I1 to O1 will pay the same toll amount as someone who travels through the entire HOT facility. This can be unfair to the drivers who travel short distances on the HOT lanes. On the other hand, travelers can choose just once whether or not to use the HOT lanes and know in advance exactly how much they are going to be charged.

  Origin-specific tolling was implemented on SR-167 HOT lanes, so users of the SR-167 HOT lanes pay the toll displayed at their entrances even if they traverse the entire facility.

- OD-based tolling implies that the toll rate a motorist will pay depends on where he or she enters and leaves the HOT lanes, i.e., it is based on their origin and destination. Thus, there is a different price for motorists who travel through different OD pairs. In this case, the prices to major destinations should be displayed at the variable message sign prior to each entry point so that motorists can decide whether they want to use the HOT lanes. In the example network of FIGURE 3.32, there are seven OD pairs (I1-O1, I1-O2, I1-O3, I2-O2, I2-O3, I3-O2, I3-O3) and drivers have to pay depending on their OD. The toll per mile can be different for different OD pairs, thus creating some equality issues among drivers. The tolls displayed before each toll gantry show the price to major destinations, but do not indicate the exact amount a driver will finally pay. This toll structure is implemented on I-15 in San Diego.

- In distance-based tolling, the toll amount a motorist is charged depends on the distance that he or she travels on the HOT lanes. The toll rate, that is, toll per mile, is the same for all entry locations at a specific time interval. The variable message sign at the entrance should display the minimum toll for entering the facility (the toll to the first exit), a toll rate, and the toll amount for traveling to the end of the facility. For example, in FIGURE 3.32, the toll per mile for all the three entrances, I1, I2, and I3 will be the same at a certain time interval. At each entrance, the toll per mile is displayed. Such a toll structure has been recently implemented on I-85 HOT lanes in Georgia.

The pros and cons of the above four toll structures are summarized as follows. In the zone-based tolling, the toll charged for one zone is usually determined based on the traffic conditions in that particular zone. The toll rate will be displayed at the entrance to each zone. Therefore, the tolling algorithm for each zone is essentially the same as for a single-segment facility. In this sense, the zone-based toll structure is easier to implement. Motorists can make their decisions on whether to pay to access the HOT lanes multiple times and they know in advance exactly how much they will pay when they make those lane-choice decisions. One of the critical issues in implementing a zone-based toll structure is to determine the number and location of zones. If a zone is too long, pricing becomes less effective in managing demand. Conversely, many short zones will create additional lane changes, possibly yielding moving bottlenecks and disrupting the managed lane operations.

To summarize, origin-specific tolling is convenient for users because they only need to make their lane choices once. However, this toll structure may create inequity if the facility is long because the toll per mile at an upstream entrance may be less than that at a downstream entrance. Otherwise, the capacity of HOT lanes upstream would be wasted. Consequently, users who enter midway or downstream of the HOT lanes may pay more for traveling a shorter distance, which may be viewed unfair to many. Similar to some ramp metering strategies, this toll structure tends to favor the long-distance travelers. If not designed properly, it may lead to public resistance, like the opposition to ramp metering in the Twin Cities, Minnesota, area where the state legislature passed a bill in 2000 requiring a ramp meter shut-off experiment.

The OD-based toll structure, at least theoretically, can effectively manage demand and utilize available capacity on a long multi-segment HOT facility. The toll rates can be carefully designed to reduce inequality among users who access the facility via different entrances. It is, however, more sophisticated and thus more difficult to implement than the previous two structures. It can require a relatively high implementation cost because the system should keep track of where the vehicles enter and exit. Another downside of this structure is that, when users make their lane choices, they may not be sure of the exact amount of toll they will have to pay for their trips. In the current practice on freeways (i.e., I-15 in San Diego), when a motorist enters the facility, he or she needs to pay the minimum toll, regardless of his or her destination. A sign at each entrance advises one or more possible fares for longer trips to upcoming exits. If the destination is somewhere after the first possible exit, the expected toll can fall between the minimum and the toll for traveling all the way to the last exit of the HOT lanes.

When compared to OD-based, the distance-based toll structure seems easier to implement. Software for implementing both schemes have similar complexity. However, distance-based tolling is more flexible at managing the traffic demand and may not create much equity concern as all travelers pay the same rate per-mile. On the other hand, distance-based tolls may lead to an inefficient use of the managed lane capacity.

TABLE 3.4 summarizes the advantages and disadvantages of the different toll structures presented above.

TABLE 3.4 Pros and Cons of Toll Structures

Toll structure	Pros	Cons
Zone-based	Easy to implement, particularly when expanded from a single-segment HOT facility	Additional lane changes at the beginning of each zone may cause disruptions; difficulty of balancing utilization of capacity and the disruptions caused by lane changes
Origin-specific	Easy to implement and convenient for users	Inefficient utilization of capacity possible inequality concerns
OD-based	Effectively manage demand and utilize capacity	More costly to implement
Distance-based	No equity concern	More costly to implement inefficient utilization of capacity

The selection of a toll structure to implement depends on the HOT or ET lane configuration, demand patterns, and available resources. All four toll structures have been implemented for HOT lanes on freeways. However, there is no implementation on arterials. Generally, a HOT or ET lane facility on an arterial is expected to have more entrances and exits comparably to a freeway HOT or ET lane facility and thus there are more OD pairs and more lane choice decision points for the travelers. Also, it is expected to be used for shorter trips. Thus, even though all four toll structures could theoretically been implemented on a multi-segment HOT/ET lane on an arterial, some toll structures could provide more overall benefits than others. For instance, if the HOT/ET facility is long and many exits, then the origin-specific toll structure could create noticeable inequity issues. On the other hand, the OD-based toll structure could be too complicated and cause unnecessary confusion. Therefore, the zone-based or even distance-based structure is more appropriate for an HOT/ET lane on arterials.

3.3.2.2 Speed Limit

Setting limits for a speed of traveling vehicles is a widely used and effective tool reducing traffic accidents and prevent road casualties. An operating speed method or a road risk method can be used to determine speed limits for arterial managed lanes. In addition, it is critical to limit the maximum speed differential between the managed and GP lanes in advance of access points. Otherwise, there is an increased chance of rear-end accidents when vehicles merge into or diverge from the managed lanes at access points. AASHTO (2004) suggested that the difference of speed limits should be limited to 10 mph to 15 mph.

Recently, many countries have adopted variable speed limits as a strategy for controlling freeway traffic. By dynamically changing the posted speed limits in response to the prevailing traffic, road or weather condition, variable speed limit systems are believed to be able to harmonize traffic flow, reduce the number of vehicular crashes and postpone or prevent traffic congestion. Recently, FDOT District 5 launched a variable speed limit system on a 10-mile stretch of I-4 from Orange Blossom Trail to Maitland Blvd in downtown Orlando.

Variable speed limits can also be implemented on arterial managed lanes, primarily for safety considerations. For example, lower speeds can be imposed during a severe weather condition. Given that the operations of arterial managed lanes are frequently interrupted by traffic signals and turning movements at intersections, variable speed limits should not be deployed for the purpose of preventing traffic flow breakdown or eliminating shockwaves, as they are expected to achieve at freeways (e.g., Carlson et al, 2010).

3.3.3 Automatic Enforcement

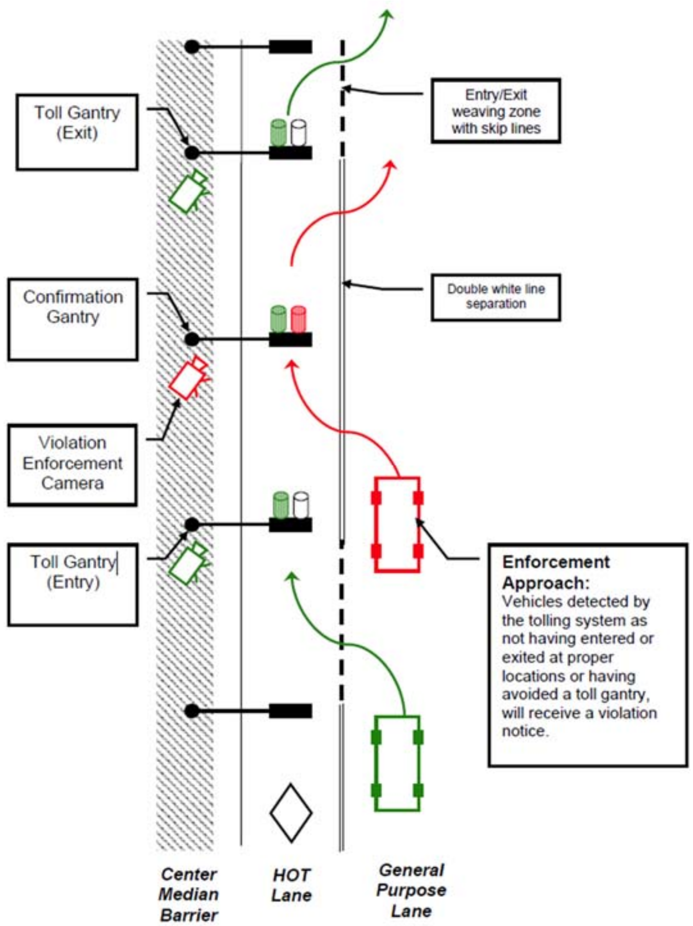
Enforcement is critical for a successful operation of managed lanes. Effective enforcement deters unauthorized vehicles and thus maintains travel time savings of eligible vehicles. In practice, effective enforcement also improves safety and helps in gaining further acceptance of managed lanes among users and non-users (TTI, 2006; Vu et al., 2008).

Vehicle eligibility violations and unauthorized entries/exits are common occurrences among managed lanes. As reported in Vu et al. (2008), the eligibility violation rate during peak periods in Atlanta is approximately 12% and, on average, there are 3.69 unauthorized entries/exits per 100 feet per hour during rush hours on an HOV lane with continuous access along the I-85 Northeast corridor.

Although it is challenging to remotely determine whether a vehicle in managed lanes carries the required number of passengers, there are a few automatic vehicle occupancy enforcement technologies. For example, near-infrared cameras (see FIGURE 3.33) are able to detect the number of passengers in a vehicle automatically and accurately. Another example is the monitoring system with two cameras: one for capturing the front windshield view and the other for the side window view (Vu, et al., 2008). After detection, the license plate of the violation vehicle will be photographed and the notice of punishment will be sent to the driver automatically.

An electronic barrier system, called Gantry Controlled Access, can be applied to enforce unauthorized entries or exits (Vu, et al. 2008). The system records the presence of vehicles at each station and then identify whether a vehicle enter or leave the managed lane illegally (see FIGURE 3.34). When a vehicle is recognized as unauthorized, it will be recorded by the system via license plate readers and a video enforcement system. Similarly, the notice of punishment will be sent automatically. Such system is reported to be deployed in I-85 express lanes in Atlanta (Perez et al., 2012).

FIGURE 3.33 Near-Infrared Cameras[15]



Source: Vu et al. (2008)

FIGURE 3.34 Example of GCA in A HOT Lane

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[15] Source: http://license.umn.edu/technologies/99201_near-infrared-detection-of-humans-in-hov-lanes

3.4 Selection and Screening Process

In this section, we propose a procedure for screening arterial corridors for managed lane implementations and then select the appropriate managed lane strategies for specific corridors. The flowchart for the procedure is displayed in FIGURE 3.35 In a nutshell, our selection and screening procedure starts with the identification of qualified corridor and follows by the selection of managed lane type and traffic management schemes. Note that the selection and screening process is carried out in the pre-planning stage as discussed in Section 4.

3.4.1 Criteria for Qualified Corridors

This subsection establishes criteria that can help identify corridors with higher priority to implement a managed lane strategy. The key is to evaluate whether the congestion at a major corridor is severe enough to warrant a managed lane treatment. The criteria are listed below. Note that the evaluation is not limited to existing conditions. It should also consider the future transportation needs (http://www.flfuturecorridors.org/index.htm).

- High traffic volume: A corridor should have enough traffic volume to justify a managed lane treatment. If the current traffic volume is low but expected to grow substantially in the future, the corridor can also be a good candidate. In Parsons Brinckerhoff and TTI (2009), it is suggest that a corridor can be qualified for a managed lane treatment, if the average annual daily traffic is greater than 10,000 × number of lanes.
- High level of congestion during peak hour: One of the primary goals of deploying managed lanes is to mitigate traffic congestion. Therefore, if a corridor experiences a high level of congestion, it may be considered as a candidate for managed lane deployment. Threshold values were suggested as the level of service of E or F for two hours or more, or a travel speed of 20 mph or less for two or more consecutive hours (Parsons Brinckerhoff and TTI, 2009).
- Importance to a managed lane network: If a managed lane facility on a corridor is critical to the continuity and connectivity of a managed lane network, its deployment may thus be justified.

If one or more criteria listed are satisfied, the corridor is considered to be qualified. Assuming that it is financially and physically feasible to deploy a managed lane along the corridor, below we discuss the process of determining a particular managed lane strategy to implement.

3.4.2 Managed Lane Selection and Screening Process

First, determine whether an HOV lane exists and its utilization is less than a certain threshold value.

Lou et al. (2011) suggest that converting an HOV to an HOT lane is beneficial when the HOV demand is lower than 80% of the capacity of the lane. If the HOV lane is congested, i.e., the demand has exceeded its capacity, adding an additional HOV lane or increasing the occupancy requirement may more effective.

Second, if the HOV demand is sufficiently high, a new HOV lane can be considered. Parsons Brinckerhoff and TTI (2009) suggest that the HOV demand should be higher than 300 vphpl while Turnbull (2002) suggests 200 to 400 vphpl for both right-side and left-side HOV lanes and 80 to 160 vphpl for a reversible HOV lane.

Third, if many local buses are serving the corridor and their performances need to be further enhanced, then a bus-only lane can be considered. Turnbull (2002) suggests that a minimum bus volume of 50 to 80 vphpl is required to justify a bus-only lane.

Finally, if the corridor is long enough and intersections are apart from each other, a HOT or ET lane should be considered. Without substantially reducing accessibility, turning movements at some intersections may be prohibited or the intersections can be entirely removed to further enhance the performance of HOT or ET lane.

After selecting the type of the managed lane, the process proceeds to the determination of traffic management schemes, more specifically, treatments at selected intersections that operate under saturation.

Improving signal control, such as changing signal timing, can be first considered as it is relatively easier to implement. On the other hand, the deployment of a transit signal priority system is much more involved. It can be considered if it is of critical importance to improve the service quality of bus routes using a bus-only lane. Queue jumps can be constructed to further enhance the performance of the managed lane, particularly if the lane is HOV or bus-only. Parsons Brinckerhoff and TTI (2009) suggest that if there are at least 20 buses or 200 vehicles per hour per lane, a queue jump may be worth implementing.

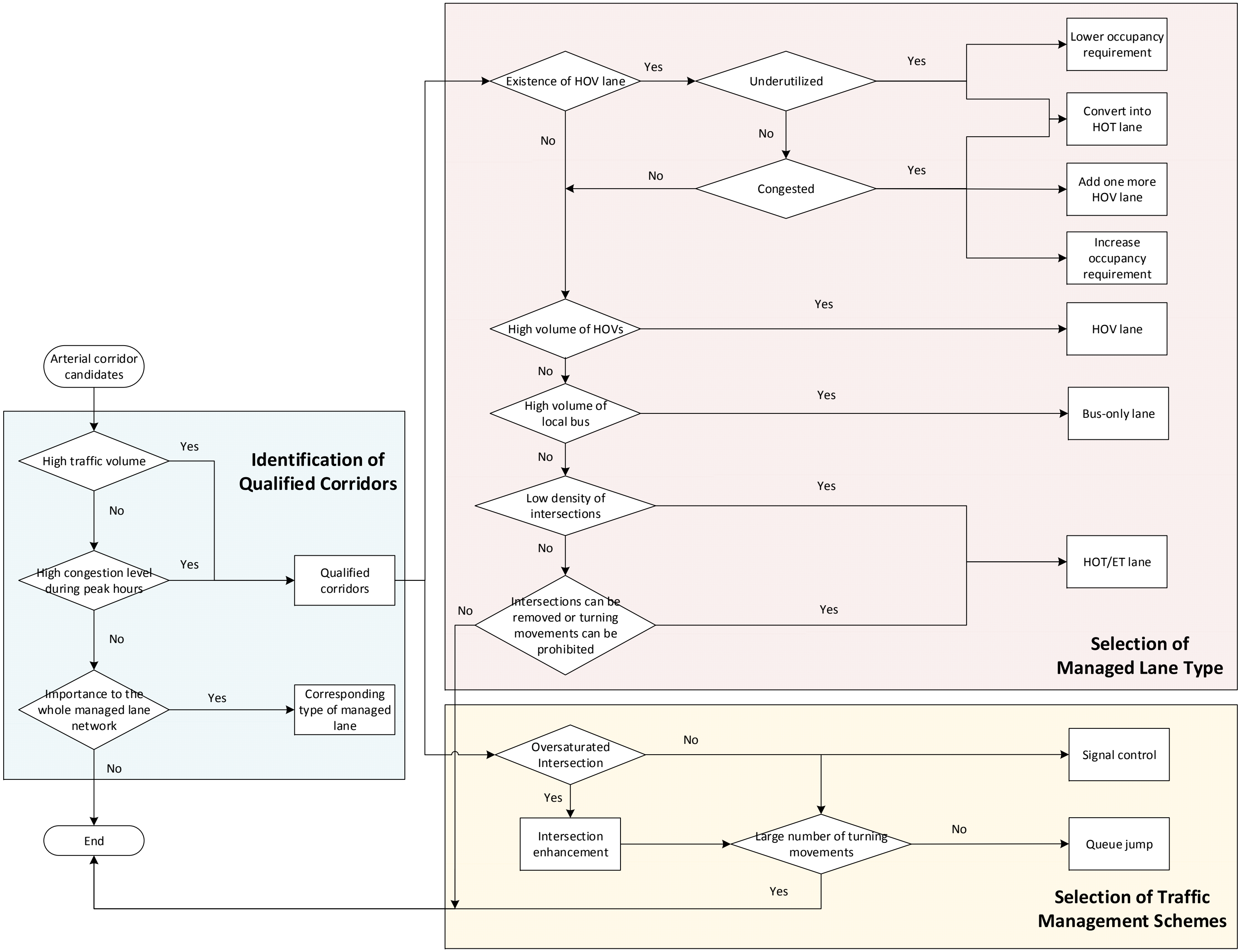


FIGURE 3.35 Flowchart of Selection and Screening Process

4 IMPLEMENTATION AND MONITORING PROGRAM

4.1 Introduction

Planning and implementation process is important in ensuring the success of any project. Below, we describe the planning and implementation process of managed lane projects on arterials. (see Section 3 for the different types of managed lanes suitable for arterials.)

4.2 Overview and Milestones

The overall planning and implementation for managed lanes consist of the following steps (Perez et al., 2012):

1) **Pre-planning**: Once the need for managed lanes is identified, the responsible transportation agency—often in coordination with the local MPO and using the Context Sensitive Solutions (CSS) approach (see Section 4.3 for details)—develops and reviews conceptual, operational, and physical solutions or projects for their effectiveness, anticipated cost, ease of implementation, and acceptability to the public. The decision to proceed with the improvement project should be weighed against other needs facing the state and local region.

   According to Grant et al. (2011), metropolitan areas with population exceeding 200,000 are considered as Transportation Management Areas or TMAs. Federal regulations require TMAs to conduct a Congestion Management Process (CMP) as an integral component of metropolitan transportation planning. (See Section 4.3 for details about CMP.) The decision to proceed with a managed lane project in a TMA should be an outcome of a CMP.

2) **Planning**: If the project sponsor makes a decision to proceed with the project, the project should be incorporated into the MPO's long-range MTP that identifies transportation needs and policies over a 20-year horizon. Once in the MTP, federal funding may be used to support planning work and the completion of NEPA environmental clearance documents. During this process, the project sponsor should narrow and refine the project as well as develop alternatives.

   The process culminates with the identification of a preferred alternative that must be approved through a Categorical Exclusion, a FONSI upon the completion of an Environmental Assessment, or a ROD upon completion of an EIS. Projects must also be incorporated into the MPO's TIP, a fiscally constrained plan that identifies the projects in the MTP to be completed in the coming four-year cycle.

3) **Design and Procurement**: Once the MPO and NEPA requirements and funding commitments have been completed and secured, the project sponsor completes design work for the preferred alternative and then puts the project out to bid.

   If the project is being procured via the traditional DBB model, the project sponsor would retain a design consultant to complete the final design drawings and hold a second procurement for project construction. The qualified contractor submitting the lowest bid is awarded the project. Alternatively, if the project sponsor chooses to procure the project on a DB or DBFOM concession basis, a design-builder or private concessionaire normally completes the final design work. The sponsor must also perform additional analyses to determine if DBFOM procurement is feasible. These would include conducting a financial feasibility analysis to determine the "base financial case," i.e., the cost if the project sponsor builds, operates, and maintains the project. Toll proceeds should be forecasted to see whether they would be sufficient to finance the project. If offers submitted by private developers are better than the base financial case, then the best offer delivers a better value and should be accepted. (When two or more offers are the best, use other factors such quality and past performance to break the ties.)

4) **Construction**: During the construction phase a private contractor, design-builder, or private development partner builds the project according to the design specifications and implementation schedule established in the construction contract. The project sponsor supervises the construction to ensure that it will be consistent with the design and meets the necessary quality standards.

5) **Operation and Maintenance**: Once completed to the satisfaction of the project sponsor, the new facility begins its operation. With traditional DBB or DB procurements, the project sponsor assumes responsibility for maintaining and operating the managed facility. With DBFOM concessions, the private developer operates and maintains the facility for a designated concession period. During this period and depending on the project, the private developer has the right to collect toll revenues or receive availability payments from the project sponsor. In some cases, the project sponsor or other public toll agency might be responsible for toll collection. Responsibility for enforcement and incident management remains with the appropriate public agencies.

In the following page, Figure 4.1 displays the planning, implementation, and milestones of a managed lane project as a flowchart. To fit the entire process on a single page, we combine several steps into one box in places. Subsequent sections elaborate more on steps in the figure.

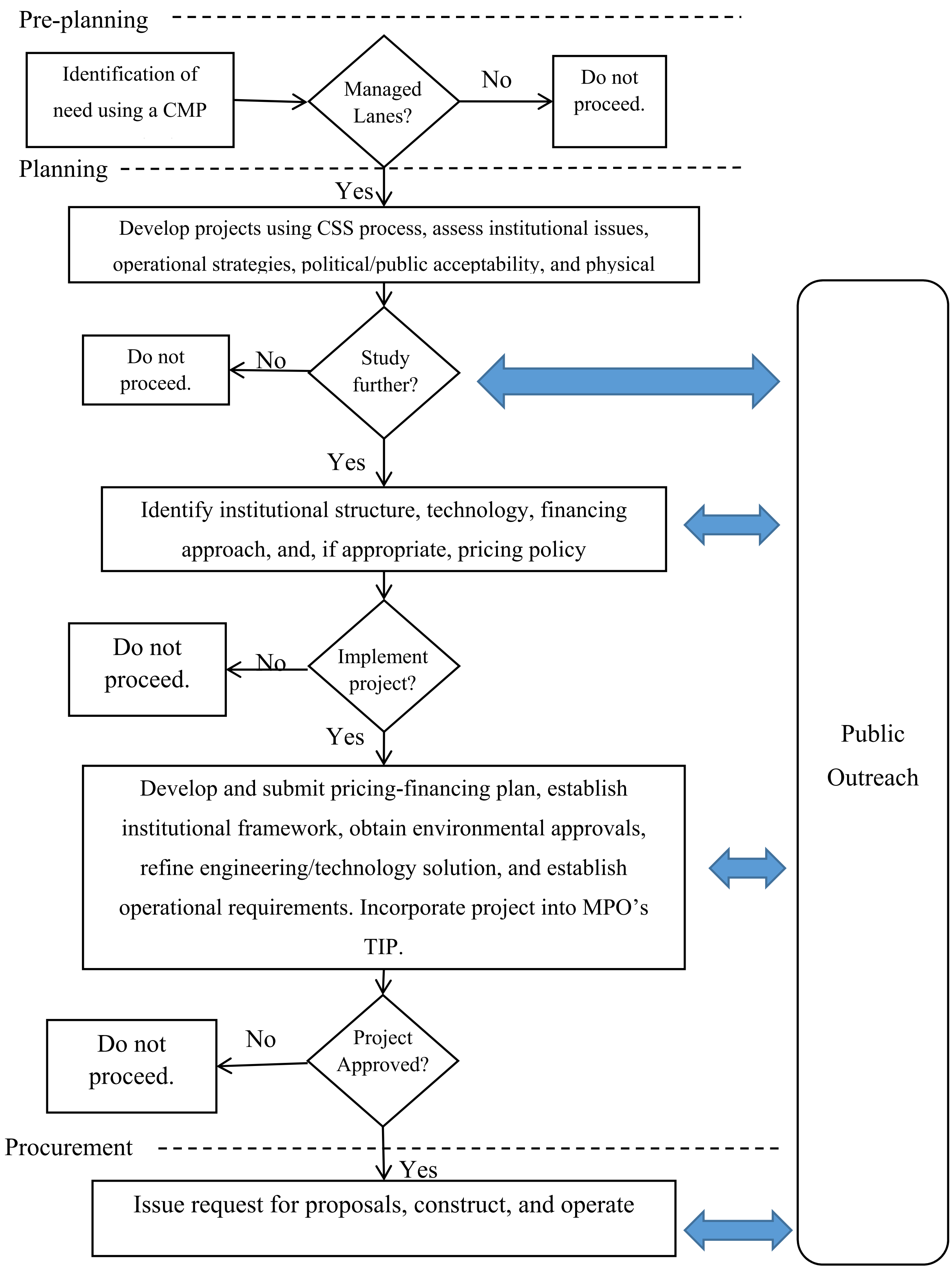


FIGURE 4.1 Proposed Planning and Implementation of Managed Lanes

From Figure 4.1, the following milestones can be identified:

1) Decision to investigate a managed lane solutions at the end of the pre-planning phase (6 months to one year)
2) Decision to study a managed lane concept after assessing the institutional issues, operational strategies, political and public acceptability, and the physical constraints such as space availability and geographical suitability (6 months to one year)
3) Decision to implement a project after identifying institutional structure, preferred engineering and technologies, financing approach, and pricing/eligibility policies (1 to 3 years)
4) Development and submission of pricing-financing plan, establish institutional framework, obtain environmental approvals, refine engineering/technology solution, and establish operational requirements for review and approvals at city, county, district, state, and federal level (1 to 3 years)
5) Issuance of a request for proposals
6) Contractor/concessionaire selection (6 months to one year)
7) Beginning of construction after finalizing institutional structure, preferred engineering and technologies, and preferred financing approach (up to 5 years)
8) Facility opening after construction is completed, inspected for compliance with design, engineering, and quality standards, and accepted by responsible agency (1 to 6 months)
9) Annual performance review (every year)

In Figure 4.1, public outreach and consensus-building activities are critical throughout the process of planning and implementing managed lanes, particularly those managed by price, because of the following challenges:

- While the benefits of combining occupancy requirements, access, and price to manage demand bring clear transportation benefits, the concept is often difficult for political decision makers and the public to embrace.
- Many perceive tolling as double taxation because other transportation needs are funded with motor fuel taxes, vehicle registration fees, and other tax revenue.
- Equity is a key concern with lanes managed by price, as some stakeholders may believe that it is inequitable to provide premium service to those who appear more likely to afford it.

4.3 Identification of Need during Pre-Planning[16]

The identification of general needs, issues, and opportunities for transportation improvements begins at the regional level with inputs from representatives of the MPO, state DOT, transit agency, affected federal agencies and local communities.

4.3.1 Congestion Management Process

For metropolitan areas with populations of at least 200,000, this identification of needs, issues, and opportunities should be a natural consequence of an on-going CMP mentioned in Section 4.3.1, which is a federal requirement. A CMP is a living document that evolves continually to address concerns of the communities, objectives and goals of the MPO, and congestion issues at the present and in the future. A CMP typically consists of the following eight actions (Grant et al., 2011):

[16] The content of this section is adapted from Parsons Brinckerhoff and TTI (2009).

1) <u>Develop regional objectives for congestion management</u>: In developing objectives, it is important to realize that it may not be feasible or desirable to eliminate all congestion. Two questions that need answers are “What is the desired outcome?” and “What do we (MPO) want to achieve?”

2) <u>Define CMP network</u>: This action involves specifying the geographical boundaries and system elements to be considered such as freeways, arterials, and transit routes.

3) <u>Develop multimodal performance measures</u>: This action addresses the question: “How do we define and measure congestion at both regional and local scale?” For example, congestion can be defined using volume-to-capacity ratios or level of service (LOS) in combination with factors such as intensity, duration, extent, and variability.

4) <u>Collect data and monitor system performance</u>: After performance measures are defined, data should be collected and analyzed to evaluate and/or assess the effectiveness and efficiency of the CMP network in managing congestion.

5) <u>Analyze congestion problems and needs</u>: The purpose of this action is to identify locations with congestion problems and their sources. For example, the latter can include locations of major trip generators, may be seasonal, and depend on time-of-day.

6) <u>Identify and assess CMP strategies</u>: Data and analyses from Action 4 and 5 should evolve into a set of recommended solutions to effectively manage congestion and achieve objectives established for the region. (When strategies involve managed lanes on arterials, the procedure or flowchart documented in Chapter 3 can be used.)

   An approach for accomplishing this action involves using the CSS which is a collaborative, interdisciplinary, holistic approach to the development of transportation solutions or projects. It is both a process and product characterized by a number of attributes. (see, FHWA, 2007.) It involves all stakeholders, including community members, elected officials, interest groups, and affected local, state, and federal agencies. It puts project needs and both agency and community values on a level playing field. CSS considers all trade–offs in decision-making and should be a part of all phases of program delivery including long-range planning, programming, environmental studies, design, construction, operations, and maintenance.

7) <u>Program and implement CMP strategies</u>: Implementation of CMP strategies occurs on three levels: system or regional, corridor, and project. Implementation of strategies at a regional level requires their inclusions in the MTP and/or TIP as discussed in Section 4.2. At the corridor level, strategies such as bicycle and pedestrian improvements can be assessed in studies and implemented using a variety of funding sources such as Surface Transportation Program (STP), National Highway System (NHS) funds, the Congestion Mitigation and Air Quality Improvement (CMAQ) Program, and Transportation Alternatives Program (TAP). Section 4.7 provides discussion concerning funding sources specific to managed lane projects.

8) <u>Evaluate strategy effectiveness</u>: The primary goal of this action is to ensure that implemented strategies are effective at addressing congestion as intended and to make changes based on the finding as necessary.

4.3.2 Alternative Approaches for Non-TMAs

For metropolitan areas with population less than 200,000, a CMP is not required. However, FHWA publications recommend similar approach to identify the need for transportation improvement. As an example, below is a process described in Perez et al. (2012).

The regional planning process involves a screening of the potential for facility improvements based on a review of existing and forecast travel conditions when compared to a set of baseline and forecast transportation improvements. The purpose of screening is to determine if specific conditions, including the presence of congestion, travel-time benefits and demand, are present to support a managed facility. The screening process may involve successive steps to identify candidate corridors, growth patterns, and future conditions that are appropriate. Criteria used at the screening stage tend to be qualitative and take into account both the availability of data and need to examine issues on the macro level and allow for variances in corridors and market needs. For example, screening criteria at regional level include the following:

- <u>Congestion</u>: Understanding of congestion in the region requires knowing the length and duration of traffic queues, weaving and accident characteristics associated with recurring and non-recurring events in, e.g., corridors, neighborhoods, and arterials.
- <u>Travel-Time Saving</u>: Estimating the potential travel-time savings is important in being able to assess overall cost effectiveness. A general guideline is that a managed lane should generate at least five minutes of travel-time savings before a mode shift starts to occur.
- <u>Travel-Time Reliability</u>: Providing trip reliability, based on observed frequencies of accidents and incidents, is another important factor influencing user behavior in a managed facility. Reliability is also important to transit providers in providing a reliable transit service.
- <u>Transit Services and Facilities</u>: Where transit service potential exists, a market analysis may be needed to determine the nature of transit demand for express bus and park & ride services. An assessment would define where demand is located, what size facilities would be needed to serve it, and what access requirements to a managed lane will be needed to best serve the demand once specific alternative sites are identified.
- <u>Demand</u>: Choosing a specific design and operation should depend on the demand from prospective users such as transit buses, carpoolers/vanpoolers, and solo drivers if pricing is considered. Each group will exhibit different travel patterns, access needs, and elasticity with respect to prices and factors such as location and frequency of service. Peak-hour demand estimates are needed for each prospective group, including motorcycles and possible hybrid vehicles, based on the latest federal statutes.
- <u>Environmental Issues</u>: Assessing the possible benefits and issues at a preliminary level of detail can be used to examine alternative designs and operational approaches.
- <u>Cost Effectiveness</u>: The proposed facility (including dedicated lanes, ramps, and related improvements) should be subject to an assessment of cost effectiveness based on its costs, benefits and impacts. For example, basic benefits include reduced delay, fuel consumption, emissions, and, when applicable, transit operating-costs. Costs include initial capital, daily operation, and maintenance.
- <u>Financial Viability</u>: A vast majority of managed lane projects and systems being proposed are unfunded or inadequately funded. An early assessment of cost and financial viability is

needed to determine if pricing the roadway must serve as both a management and revenue augmentation tool.

- Enforceability: Each design and operational concept generates a different set of enforcement issues that need to be addressed, preferably in the corridor planning stage with affected police agencies. The specific enforcement needs and potential resolutions will influence the facility design, its access plan and its operation plan.
- Phasing/Constructability: The added lanes must be able to generate meaningful benefits if opened incrementally and must be incrementally developed so that added capacity does not diminish benefits for using the lanes.
- Safety/Incident Management: Considering a managed facility provides both opportunities and potential obstacles to incident management.
- Compatibility with Other Plans and Services: Other highway and transit plans are important factors. Managed facilities should be reviewed and evaluated in a context of achieving the best efficiency among all plans and providing maximum benefits to each.
- Public and Agency Acceptance: Adequate outreach should be performed to determine if managed facilities are supported by other resource and respective transportation agencies and entities.
- Operational Impacts: A variety of site-specific impacts (e.g., relating adjacent roadway operations, intersecting streets, and intersections) may be identified.
- Other: Local criteria such as land use impacts, environmental or community concerns, safety or performance may be of concern to agency stakeholders and the public and should be investigated.

4.4 Institutional and Organizational Issues[17]

Several institutional and organizational issues need to be resolved when launching a managed-facility project. These involve identifying a logical project sponsor, arranging funding, working out operational protocols, and determining what legal ramifications may be involved.

4.4.1 Roles and Responsibilities

TABLE 4.1 lists activities associated with a managed-facility project and indicates the potential entities responsible for each activity. Not all activities (e.g., toll collection and billing) apply to every project. In some cases, a single agency, such as a state DOT, may be responsible for many of the activities noted in the table.

[17] The content of this section is adapted from Perez et al. (2012).

TABLE 4.1 Activities and Responsibility for Managed-Facility Projects

	State DOT and its district offices*	Turnpike/Toll Authority*	MPO and Other Local Agencies*	Transit Agency*	Private Development Partner	Private Consultant Contractor	Law Enforcement Agency/Emergency Response
Project Development							
Planning/Technical Studies	X		X	X	X	X	
Education and Public Outreach	X	X	X	X	X	X	
Federal Programs and Grant Applications	X	X	X	X			
Environmental Review/Permitting	X	X		X		X	
Project Finance	X	X	X	X	X		
Contract Award and Administration	X	X	X	X	X		
Design	X				X	X	
Construction	X				X	X	
Operations							
Toll Collection and Billing	X	X			X	X	
Facility Operations	X	X	X	X	X	X	
Performance Monitoring/Management	X	X	X	X	X	X	
Traffic Management Centers	X	X				X	
Travel Information	X	X		X		X	X
Maintenance Operations	X	X			X	X	
Enforcement		X		X			X
Incident Management	X	X	X			X	X
Customer Service	X	X	X	X	X	X	
Marketing	X	X	X	X	X	X	
Transit Operations			X	X			

*Indicate potential project sponsor

4.4.2 Project Sponsor

Identifying a project sponsor is one of the first and most important issues to resolve in implementing a managed-facility project. The project sponsor plays the most significant role in project implementation. As shown in TABLE 4.1, a project sponsor can be responsible for nearly all activities during a project's development and operation. The project sponsor often executes planning studies, submits applications and environmental documentation, and oversees the construction and possibly the ultimate operation of the facility. To ensure success, a project sponsor often has to champion the project, promote collaboration and participation of various stakeholders, and be the main liaison between the project and other organizations.

A state DOT frequently acts as the project sponsor, but turnpike and toll road authorities, local transportation agencies and authorities, and public transit agencies can also sponsor or co-sponsor a managed-facility project. Often a long legacy of institutional relationships has been established among project participants. Therefore, it is important to understand these relationships and determine if any pre-existing political or institutional issues should be addressed.

4.4.3 State Departments of Transportation

As the primary providers of highway service and owner/operators of a majority of the nation's managed lane projects, DOTs and/or their district offices are logical sponsors of new managed facilities on arterials. They have extensive experience in planning, designing, constructing, operating, and maintaining highways and similar facilities. They have the financial depth to contemplate building, e.g., new capacities on freeways and arterials and to obtain the expensive toll collection and traffic monitoring systems that price-managed facilities require. DOTs also have the power of eminent domain.

While state DOTs have a wealth of highway experience, they may not necessarily have the legal authority to levy tolls. They also may not be familiar with the operation of tolled facilities and the sophisticated electronic toll collection traffic monitoring systems that price-managed facilities require. In some cases, they may have limited legal authority to privatize these operations. Toll-road operation also involves back-office activities including auditing, credit-card billing, and customer service, all of which may be new activities for many DOTs.

4.4.4 Turnpike and Toll Road Authorities

As a precursor to the interstate highway program, many states developed turnpike and toll authorities with specific legislative charters to finance, build, and operate limited-access, high-speed highways. While the advent of the interstate program provided a dedicated federal motor fuel tax to provide funding for non-tolled highways, most legacy toll authorities continue to serve their original roles. Fiscal constraints beginning in the 1980s have led to renewed significance and presence of toll authorities, especially in fast growing areas such as California, Texas, Colorado, Florida, and North Carolina. Some of these authorities are state or county agencies, while others are joint entities formed by multiple jurisdictions. In certain cases, the involvement of turnpike and toll authorities may facilitate the implementation of a price-managed facility. In addition to engineering and construction experience, they are already vested with the legal authority to operate tolled facilities, thereby obviating the need to seek special authorizing legislation. Turnpike and toll authorities have the staff and systems in place to conduct all back-office revenue handling and accounting activities. In addition, many operate the advanced electronic toll collection and traffic-monitoring systems that price-managed facilities require. Because motorists are accustomed to paying tolls to turnpike and toll-road authorities, their involvement in the operation of price-managed projects could help in gaining the public's understanding and acceptance of these potential projects.

4.4.5 Local Transportation Agencies and Authorities

In order to receive federal funding for transportation projects, all urbanized areas in the United States are required to establish an MPO. MPO status is designated by the United States Department of Transportation (USDOT) and is usually given to regional Councils of

Government or other joint powers' authorities. These groups are generally governed by a board of elected officials representing municipal governments within their jurisdictions. State DOTs sit on all MPO boards *ex officio*. The organizational structure of MPOs varies around the country, and in certain cases, MPO status is given to county or municipal governments. In some areas, local authorities have been created to assist MPOs in securing funding and implementing projects identified through the MPO. These transportation or funding authorities, created at the county or regional level under varying conditions, can help to study the merits of price-managed facilities and secure funding for their implementation. Once a project is operational, they may be responsible for disbursement of net revenues collected.

Given their regional mandate and their planning function, MPOs and local transportation authorities may be logical sponsors of managed lanes initiatives. Their active and consistent support is also essential if a new managed lane is to be built, and local transportation authorities often play a primary role in the initial planning studies investigating the feasibility of such projects.

4.4.6 Public Transit Agencies

Public transit agencies present interesting opportunities for participating in price-managed facility project. Several transit agencies operate bus-rapid-transit or bus-only facilities that have excess capacity that could be sold to carpoolers, vanpoolers, or single occupant vehicles and operate as a HOT facility. Utilizing additional roadway capacity for other vehicles can help win political and public support and may limit the need to add additional roadway capacity. Similarly, the participation of transit agencies in price-managed facility projects sponsored by other agencies highlights the potential for price-managed facility projects to provide opportunities for promoting reliable mass transit improvements. Finally, transit agency involvement in the development of price-managed facilities may also help to introduce new sources of capital funds. In return, revenues for price-managed facilities can provide important new revenues to support improved transit service. It is important to note, however, that transit agencies would need to obtain the backing of the FTA before being able to launch a price-managed facility project on their own.

4.4.7 Other Entities

In addition to project sponsors, other important roles and responsibilities rest with the private sector, including consultants and contractors and with law enforcement and emergency response personnel.

4.4.7.1 The Private Sector

The fact that price-managed facility projects generate toll revenues also introduces the possibility that they could be financially independent or even profitable ventures of potential interest to private investors. Private sector involvement can be an attractive option for transportation agencies, as it provides access to additional sources of capital. This allows DOTs to reserve their own funds for other needs and often accelerate the implementation of partnership projects. Private operators are motivated to maximize efficiency in order to maximize profits and their services—both capital construction and roadway operation—can bring good value for money. On the down side, financing terms for private investors may not always be as attractive as those available to the public sector, and have the potential to offset other construction and long-term operational efficiencies.

Private consultants and contractors may play significant roles in both the project development and operational phases of a project. As with many large transportation improvement projects, technical studies, environmental review, and design may be performed by consultants. Construction services may be handled by private contractors. Specialized firms offer services in price-managed facility operations, maintenance, incident management, and back-office activities such as toll collection and billing, customer service, and marketing. Some or all of these activities may be contracted out to one or more private entities.

4.4.7.2 Law Enforcement and Emergency Response Entities

Enforcement is a critical activity in the operation of a price-managed facility both in terms of toll collection and occupancy requirements. These activities may be handled by the appropriate law enforcement agency, which could include the police force of a toll or turnpike authority, state highway patrol, or a local law enforcement agency. The decision on who will be the responsible enforcement entity will probably rest largely on established institutional protocols and precedents and may be prescribed by state law.

4.5 Federal Programs and Requirements

4.5.1 FHWA's Office of Operations

FHWA's Office of Operations (http://ops.fhwa.dot.gov/index.asp) provides national leadership for the management and operation of the surface transportation system. The office is responsible for FHWA's efforts in the areas of congestion management, Intelligent Transportation Systems (ITS) deployment, traffic operations, emergency management, and freight management and operations. Its program areas that are directly relevant to this project include, e.g., arterial management, congestion mitigation, corridor traffic management, and tolling & pricing program. (For the latter, see below for details.)

The Office of Operations has an initiative to reduce highway congestion through better operating the highway network. This initiative builds on the thought that more can be done to operate the transportation system so that it performs better to meet customer expectations regardless of the demands placed on it. The Office provides State and local transportation agencies with relevant products and services, as well as technical support and assistance.

4.5.2 Tolling Programs

Two federal tolling programs and several pilot programs offer states opportunities to implement price-managed facilities on federal-aid highways. Current guidance on these programs is available on the FHWA Moving Ahead for Progress in the 21st Century (MAP-21) website: http://www.fhwa.dot.gov/map21/guidance/guidetoll.cfm.

The FHWA Office of Innovative Program Delivery Road Pricing Revenue website (http://www.fhwa.dot.gov/ipd/revenue/road_pricing/tolling_pricing/) and the Office of Operations website (http://ops.fhwa.dot.gov/tolling_pricing/index.htm) also provide information and guidance on federal tolling programs.

The passage of MAP-21 made significant changes to the federal Section 129 Tolling Program including tolling eligibilities and agreement requirements. These changes have relaxed the prior, general prohibition on the imposition of tolls on federal-aid highways and formalized provisions previously available through pilot programs. Public agencies may impose new tolls on federal-aid highways in the following cases:

- Initial construction of a new highway, bridge, or tunnel
- Initial construction of new lanes on highways, bridges, and tunnels (including interstates) as long as the number of toll-free lanes is not reduced
- Reconstruction or replacement of a bridge or tunnel
- Reconstruction of a highway (other than an interstate)
- Reconstruction, restoration, or rehabilitation of an interstate highway as long as the number of toll-free lanes is not reduced

Prior to MAP-21's provisions taking effect on October 1, 2012, public authorities were required to execute a tolling agreement with FHWA to impose tolls on a federal-aid highway, but this requirement is no longer required. For toll facilities that have executed Section 129 tolling agreements prior to October 1, 2012, the terms of those agreements will continue in force.

<u>Section 166 of Title 23 HOT/HOV Lanes</u>: Under Section 166 of Title 23, existing HOV lanes may be converted to tolled operation provided that the local MPO endorses the use and amount of tolls on the converted lanes. All tolls on new lanes must be variably priced and collected electronically in order to manage travel demand. To implement tolls on an existing HOV lane, project sponsors must demonstrate that the conditions on the facility are not already degraded and that the presence of paying vehicles will not cause conditions on facility to become degraded. Ongoing annual reporting documenting conditions on the converted lanes is also required, and if the HOV facility becomes degraded the sponsor must bring the facility into compliance either by increasing HOV occupancy requirements, increasing tolls, increasing capacity, or eliminating access to paying motorists. The prior requirement to execute a tolling agreement with FHWA for HOV lane conversion is no longer in place under MAP-21, same as with the Section 129 General Tolling Program.

4.5.2.1 Toll Pilot Programs

In addition to the mainstream toll programs above, four toll pilot programs enacted prior to MAP-21 are managed by FHWA.

- <u>Value Pricing Pilot Program</u>: The Value Pricing Pilot Program (VPPP) was initially authorized in ISTEA as the Congestion Pricing Pilot Program and subsequently amended under other laws, most recently SAFETEA-LU. The program has encouraged implementation and evaluation of value pricing pilot projects to manage congestion on highways through tolling and other pricing mechanisms. The number of VPPP project is limited to 15, seven of which have been permanently reserved for state agencies that have executed tolling cooperative agreements under the VPPP. MAP-21 made no changes to the program, and no additional funds have been authorized after Fiscal Year 2012. However, FHWA encourages use of the Section 129 General Tolling Program and Section 166 HOV/HOT Lanes program wherever possible as opposed to the VPPP. MAP-21 guidance states that "requests for tolling authority under the VPPP will be limited to situations that cannot be accommodated under the mainstream tolling programs, such as the pricing of existing toll-free facilities without substantial reconstruction of those facilities."

- Express Lanes Demonstration Program: The Express Lanes Demonstration Program, created in SAFETEA-LU, permitted tolling on up to 15 selected demonstration projects to manage congestion, reduce emissions in a non-attainment area, or finance new and existing interstate lanes for the purposes of reducing congestion. Qualified projects under this program included those that implement variable pricing by time of day or level of traffic, as appropriate to manage congestion or improve air quality. The program expired on September 30, 2012, and qualified projects should proceed under the Section 129 General Tolling Program.

- Interstate System Construction Toll Pilot Program: The Interstate System Construction Toll Pilot Program was authorized under SAFETEA-LU to permit up to three existing interstate facilities to be tolled for the purpose of financing the construction of new interstate highways. Under MAP-21, the program has effectively been mainstreamed under the Section 129 General Tolling Program, and consequently, FHWA will no longer be accepting applications for this program.

- Interstate System Reconstruction and Rehabilitation Pilot Program: The Interstate System Reconstruction and Rehabilitation Pilot Program was authorized under TEA-21 to permit up to three existing interstate facilities to be tolled to fund needed reconstruction or rehabilitation on interstate corridors that could not otherwise be adequately maintained or functionally improved without the collection of tolls. MAP-21 does not make any changes to this program. In order to receive tolling authority under the program, project sponsors are required to have their program application approved by FHWA and to execute a tolling agreement. All three of the slots authorized for this program are conditionally reserved as of October 2012.

4.5.3 Major Project Requirements

Title 23 defines Major Projects as highway improvements requiring federal assistance that are over $500 million in cost. FHWA also has the discretion to designate a project with a total cost of less than $500 million as a Major Project in certain cases. At this scale, the processes and federal requirements involved in project delivery become more complex, rendering it more challenging, but ever more important, for the process to be well-managed. Several price-managed facility projects implemented to date as part of larger major reconstruction projects have qualified as Major Projects. For federal funding to be authorized for the financing of a Major Project, the project owner must demonstrate to FHWA that the project has been carefully planned out, i.e., costs have been estimated as accurately and meticulously as possible; risks have been carefully considered and mitigated; financing requirements and strategies have been clearly defined; and the implementation of the project delivery has been carefully planned. Through the different phases of project delivery, project owners are required to submit financial and management plans and are subject to undergo various FHWA review processes before federal funding can be released for the project. Additional information on Major Project requirements is available at http://www.fhwa.dot.gov/ipd/project_delivery/resources/index.htm .

4.5.4 State Processes and Requirements for Tolling

4.5.4.1 State Models

Price-managed facility projects must comply with state and local laws on toll collection. The authority to collect tolls on state highways and other roads typically rests with designated turnpike or toll road authorities in states that have such agencies. However, toll collection may be limited to roadways already operated by these agencies. Obtaining authority for toll collection on newly developed roadways or previously un-tolled roadways may require approvals beyond the agency including a state legislative body.

4.5.4.2 Variable Pricing Authority

Trust agreements governing the operation of most toll roads only allow flat point-to-point toll rates (i.e., a consistently applied toll rate from point A to point B). If a price-managed facility project involves variably priced tolls, legislation may need to be drafted that establishes how and when toll rates can be changed and establishes the minimum acceptable traffic service levels in the price-managed facility. These issues should be addressed in the enabling legislation that will establish the legal and regulatory framework for the price-managed facility. Because price-managed facility operations require a high degree of interagency cooperation and shared responsibility, enabling legislation should designate the operating agency or agencies and outline their specific responsibilities in such areas as construction, maintenance, toll collection accounting, and enforcement. If the price-managed facility were to be operated by a bi-state organization, approvals would be required from the United States Congress, as well as both state legislatures.

4.5.4.3 Public-Private Partnership Authority

Use of private financing mechanisms for transportation facilities can occur only when the necessary legal authority exists and governing legal principles and restrictions are observed. Local governments not only must have the legal power through constitutional or statutory provisions to finance transportation facilities, but they must also use this power within the legal restraints established by legislatures and courts. The methods of granting power and limitations on that power vary.

The Office of Innovation Program Delivery (http://www.fhwa.dot.gov/ipd/p3/index.htm) provide information and expertise in the use of different public-private partnership (P3) approaches, and assistance in using tools including the SEP-15 program, private activity bonds (PABs), and the TIFIA Federal credit program to facilitate P3 projects. Details concerning these tools are in Section 4.7.

4.6 Public Outreach[18]

Public outreach efforts establish meaningful processes for public participation in the planning and implementation of transportation projects and ensure that the different stakeholders have a voice in the planning process. This enables diverse interests involved to arrive at a transportation solution that is broadly accepted and beneficial. Ultimately, the goal of a public involvement program in support of a managed-facility project is to achieve consensus around

[18] The section is adapted from Perez et al. (2012)

and utilization of a program of action. While one segment of the population may strongly favor managed facilities as the solution, another segment may feel it derives little benefit from the proposed facility. As with any proposed transportation improvement, managed facilities may have documented potential for technical and operational success, but may not find unanimous approval among constituents in the corridor.

In using the public outreach process to build consensus, planners should attempt to anticipate the concerns of specific interest groups. An understanding of what aspects of managed facility projects may be more or less attractive to different groups can be valuable to project sponsors. Certain stakeholders and interest groups with a defined agenda may support or oppose a project depending on their priorities and how their town or county may be affected by the project. When sponsors understand constituents' concerns, the public outreach process can be tailored to ensure that those issues are addressed and to discuss how those concerns will or could be accommodated within the proposed project. When discussing plans to address issues and finding ways to accommodate various public concerns, staff members involving in or connected with the operational aspect of the proposed project can offer useful advice and assistance. They can make modifications, e.g., on how a managed lane will operate once the construction is completed and may be able to better explain them to the public.

Stakeholders may possess a range of opinions about a project, but consensus on a course of action is more likely if the public has been engaged in discussions of all the issues and if stakeholders agree upon the following:

- A serious congestion problem exists and should be addressed. Conventional solutions like adding additional GP lanes, building transit facilities, or applying short-term or site-specific transportation systems management strategies may not be sufficient.
- Travel-time reliability in the corridor is desirable.
- Given the sponsoring agency's mission, it is the right entity to address the situation.
- The sponsoring agency's approach and proposed solution to the problem is reasonable, sensible, responsible, and fair.
- The sponsoring agency listens to and cares about local stakeholders.

4.6.1 Stakeholder Identification

In reaching out to local communities, political groups and organizations, elected officials, and neighboring cities, towns, and counties, project planners should include all potential stakeholders. No segment of a community likes to be excluded or surprised, and early efforts at inclusiveness will help to establish channels of communication at the outset of a managed lane project. Potential stakeholders include:

- Local residents
- Neighborhood groups and associations
- Elected officials
- Neighboring counties, municipalities, or towns
- Associations of governments
- Metropolitan planning organizations
- Area businesses

- Chambers of commerce
- Tourism representatives
- Developers
- Local and state departments of transportation
- Local and regional transportation providers
- Local and regional transit providers (public and private)
- Local and regional tolling authorities
- Local and regional law enforcement authorities
- Local and regional agencies involving in intelligent transportation systems and operations related to incident management, public and road safety, homeland security, hazard materials, etc.
- Rideshare coordinators
- Public agencies (for land use and air quality)
- Emergency service providers
- Environmental groups
- Transit rider groups
- Automobile clubs
- Taxi associations
- Labor interests
- Trucking interests
- Newspaper reporters
- Newspaper editorial boards
- Think tanks

4.6.2 Sharing Information

Keeping the variety of stakeholders well informed during the initial project planning, review, construction, implementation, and operation phases is important for consensus building. Project planners and spokespeople can use a variety of methods to keep stakeholders involved and informed. These may include the following:

- Advance notice for public meetings
- Public meetings
- Brainstorming sessions/group problem solving
- Email lists and newsletters
- Social media (e.g., Twitter, Facebook)
- Telephone information/service lines
- Project websites
- Walk-in office/customer service centers

Stakeholder coordination should continue throughout project implementation. Ensuring that technical work does not outpace constituency building is a prudent approach that keeps state, county and local politicians informed of project activities on a regular basis.

4.6.3 Citizens' Advisory Committee/Community Task Force

One option for formalizing public participation is through a citizens' advisory committee. Such committees can be effective outreach tools and they may be particularly useful for price-managed facility initiatives. Participants can be drawn from a variety of groups in the early planning stages, and the committee can help guide the public outreach process through later phases of planning and implementation. The group can be an important resource for identifying issues that outreach efforts should address and for connecting project sponsors with area community groups and other organized stakeholders. An advisory committee can also help to identify and recruit political champions.

4.6.4 Executive Advisory Committee

Some project sponsors have assembled a network of community leaders, inviting their input at key strategic points in the project progress. An executive-level advisory committee typically includes mayors, agency leaders, and other state and local elected officials. While these types of committees rarely have decision-making authority, their value is in representing their constituents, advising planners, and contributing to regional consensus. These committees may also be valuable in developing or maintaining regional consensus and helping to resolve conflicts between governments and agencies.

4.6.5 Marketing and Refining the Concept

Ultimately, the success of a price-managed facility will depend on drivers who are willing to pay to use it. In fact, some facilities refer to users as subscribers, pass holders, or customers, indicating that the facility has a clientele, and that drivers generally must acquire an electronic tag (transponder) for automated toll collection in order to use the facility.

Because price-managed facilities are generally constructed within or parallel to existing roadways, drivers in the corridor may choose which facility to use, GP or managed facilities. Project planners thus face a challenge of cultivating users for the facility and some seek the services of marketing professionals to develop and implement a marketing plan in conjunction with and parallel to the public outreach process.

The marketing aspect of price-managed facility planning is directly related to project feasibility. Marketing efforts can address how and why drivers may opt to acquire a user tag and toll account, and under what circumstances they will choose to use the facility for a given trip. Marketing techniques can be used to increase the number of users, address customer satisfaction issues, and to keep drivers well informed of any planned operational changes.

4.7 Financing Managed Facility Projects[19]

Different strategies should be pursued when financing managed-facility projects. All projects are unique. There is no single best approach. Below provides overviews of potential funding sources. For additional details concerning funding mechanism, application processes, tools, programs, legislation, and resources, see the Project Finance website[20] maintained by FHWA and its primer on project finance (FHWA, 2010). FHWA's Office of Innovation Program

[19] This section is adapted from Perez et al. (2012).
[20] http://www.fhwa.dot.gov/ipd/fact_sheets/finance_introduction.htm

Delivery (IPD) provides research, technical assistance, and policy direction that assists project sponsors in understanding and using a wide array of finance tools.

- **Federal Demonstration Funds**: The Transportation Equity Act for the 21st Century (TEA-21) permits the U.S. Department of Transportation's FHWA to enter into cooperative agreements with up to 15 State or local governments or other public authorities to establish, maintain, and monitor value-pricing projects. Any value-pricing project included under these local programs may involve the use of tolls on the Interstate System. A maximum of $7 million was authorized for fiscal year (FY) 1999 and $11 million for each of FYs 2000 through 2003 to be made available to carry out the requirements of the Value Pricing Pilot Program. The Federal matching share for local programs is 80 percent. Funds allocated by the Secretary to a State under this Section will remain available for obligation by the State for a period of 3 years after the last day of the fiscal year for which the funds are authorized.

- **State Funds**: In locations where there are no prohibitions against using state monies to construct a toll facility, state transportation funds may be used to support construction of price-managed facilities. State Infrastructure Banks (SIBs) are one of the most logical sources of state support for price-managed projects. SIBs are revolving funds that function much like a private bank and can offer a range of loans and other credit assistance enhancements to public and private sponsors of highway or transit projects. SIBs can provide loans—at or below-market rates—loan guarantees, standby lines of credit, letters of credit, certificates of participation, debt service reserve funds, bond insurance, and other forms of non-grant assistance.

  SIB support may be used to attract private, local, and additional state financial resources, leveraging a small amount of SIB assistance into a larger dollar investment. Alternatively, SIB capital can be used as collateral to borrow in the bond market or to establish a guaranteed reserve fund. Loan demand, timing of needs, and debt financing considerations are factors to be considered by states in evaluating a leveraged SIB approach.

  Most SIBs were established using Federal-aid grants and local match funds as seed money. As loans or other credit assistance are repaid, a SIB's initial capital is replenished and can be used to support new projects. Therefore the resources available to many SIBs are likely to be constrained. However, as of mid-2002 additional Federal funding for SIBs in California, Florida, Missouri, Rhode Island, and Texas provide significant new resources for SIB loans and credit enhancements in those states. Among other facilities, SIB funding has been used to support the construction of the Pocahontas Parkway in Virginia and Butler Regional Highway in Ohio.

- **Local Sales Tax Initiatives**: With shrinking federal and state budgets, local initiatives have been used successfully to fund transportation improvements. But a key to this type of funding mechanism is outlining what will be built with the money before the legislation goes to a vote so that citizens will know what they are getting. In the case of, e.g., a price-managed lane, the revenue allocation plan would also need to be spelled out before the initiative is taken to the voters so that the funds can be accounted for. People are less likely to vote to tax themselves if they feel that the money is going to go into a black hole of bureaucracy, so definition of the projects on which the money will be spent and strict accountability for the funds after they are collected is of paramount importance from the outset.

Sales taxes, while they have the potential for significant revenue generation, are also highly sensitive to economic cycles. Currently, many transportation agencies that rely extensively on this source are experiencing funding gaps, as the economy has slowed to near-recession conditions, and in response to the terrorist attacks.

Other sources of local transportation finance are also available and have been utilized; these include motor fuel taxes, motor vehicle registration taxes, commuter taxes, tax increment financing, and other forms of special assessment.

- **<u>Bonding and Debt Instruments</u>**: Several bonding and debt instrument options are available to priced managed lane project sponsors. These include municipal debt in the form of revenue bonds and Grant Anticipation Revenue Vehicle (GARVEE) bonds backed by future federal-aid funds, as well as private activity bonds and commercial bank loans in the case where a private sector partner is responsible for arranging project financing.

  – <u>Revenue Bonds</u>: Bonding is the primary financial tool available to state and local governments to raise financing covering the cost of public works projects of all types. State and local governments are able to issue debt using the municipal bond market where the interest income earned by the holders of these bonds is exempt from federal tax, as well as state and local taxes if the bonds are issued in the investor's state of residence. As a result of the tax-exempt status of the income investors receive from municipal bonds, investors are usually willing to accept lower interest rate payments compared to other types of borrowing with comparable risk. This makes municipal debt particularly attractive to state and local governments, as the interest rates are lower than other debt options.

  In the case of price-managed facility projects, municipal bonds can take the form of revenue bonds backed by future toll proceeds, which are used to make interest and principal payments to the bondholders.

  – <u>GARVEE Bonds</u>: GARVEEs are a form of debt repayable with future proceeds from federal-aid highway funds received by states under Section 122 of Title 23 of the U.S. Code. GARVEE bonds require state enabling legislation, which can be project specific or enable the use of GARVEEs to finance projects on a programmatic basis. GARVEE bonds are a state obligation even though they leverage federal-aid funding. GARVEE bonds may be used to cover the entire cost of projects or larger improvement programs; they are also often combined with other debt and funding mechanisms for larger projects.

  – <u>Private Activity Bonds</u>: PABs are debt instruments issued by State or local governments whose proceeds are used to construct projects with significant private involvement. PABs have long provided a low-cost financing option for various types of public-benefit infrastructure projects, such as ports and water and sewer projects. However, transportation infrastructure had not been eligible for Private Activity Bond financing until the passage of SAFETEA-LU, which added highway and freight transfer facilities to the types of privately developed and operated projects for which PABs may be issued. SAFETEA-LU placed a national volume cap of $15 billion for these facilities, which was unchanged by MAP-21. Private activity is permitted on highway improvement projects while maintaining the tax-exempt status of the bonds. In this manner, private participation in transportation infrastructure is encouraged because borrowing costs are reduced relative to standard commercial debt. In addition, PABs have been an attractive source of capital in a tight credit market where the issuance of commercial debt has been curtailed.

– Commercial Bank Loans: Private sponsors of priced managed lane projects may borrow money from a commercial bank or more likely a syndicate of commercial banks. Borrowing costs to private sponsors, however, are typically greater than to public sponsors, and especially in a tight credit market, PABs have been a more attractive source of debt. To date, no price-managed facility projects have used commercial bank loans as a part of a financing package.

- **Section 129 Loans**: Section 129 of Title 23 U.S.C. allows Federal participation in state loans to a public or private entity supporting the construction of toll highways and other non-tolled projects with other dedicated revenue sources, such as excise taxes, sales taxes, real property taxes, motor vehicle taxes, incremental property taxes, or other beneficiary fees.

  There are no Federal requirements that apply to how a state selects a public or private entity. Instead, this selection process is governed by state law. It is the state's responsibility to ensure that the recipient uses the loan for the specified purposes. Assuming that a project meets the test for eligibility, a loan can be made at any time. The Federal-aid loan may be for any amount as long as it does not exceed the maximum Federal share (typically 80 percent) of the total eligible project costs. States also have the flexibility to negotiate interest rates and other terms of Section 129 loans and the loans can be combined with other flexible match and advanced construction programs.

- **TIFIA**: The Transportation Infrastructure Finance and Innovation Act (TIFIA) credit program offers three types of financial assistance that could be used to support price-managed facilities:
  – Direct flexible repayment loans to cover capital construction and financing costs
  – Loan guarantees that provide full-faith-and-credit guarantees by the Federal government to institutional investors making loans for projects
  – Standby lines of credit providing secondary sources of funding in the form of contingent Federal loans. These loans may be used to supplement project revenues, if needed, during the first 10 years of project operations.

  TIFIA project sponsors may be public or private entities, including state and local governments, special purpose authorities, transportation improvement districts, and private firms or consortia. However, the overall amount of Federal credit assistance may not exceed 33 percent of total project costs. TIFIA assistance involves a competitive Federal application process. Project must meet threshold criteria to qualify, and estimated eligible costs must be at least $100 million or 50 percent of the state's annual Federal-aid highway apportionments, whichever is less, or at least $30 million for ITS projects. Project must also be supported in whole or part by tolls or other non-Federal dedicated funding sources and included in the state's Transportation Plan. If individual price-managed facility projects do not meet these minimum threshold criteria, they could still be eligible for TIFIA assistance if they were integrated with other larger regional improvements under a Record of Decision. The TIFIA website[21] provides several guideline publications and loan document templates, as well as the

[21] http://www.fhwa.dot.gov/ipd/tifia/guidance_applications/

necessary application materials for prospective applicants and borrowers. (see also, USDOT, 2013.)

- **SEP-15** is a new experimental process for FHWA to identify, for trial evaluation, new public-private partnership approaches to project delivery. It is anticipated that these new approaches will allow the efficient delivery of transportation projects without impairing FHWA's ability to carry out its stewardship responsibilities to protect both the environment and American taxpayers.

  SEP-15 addresses, but is not limited to, four major components of project delivery: contracting, compliance with environmental requirements, right-of-way acquisition, and project finance. Elements of the transportation planning process may be also involved. SEP-15 applications may include suggested changes to the FHWA's traditional project approval procedures and may require some modifications in the implementation of FHWA policy. Deviations from current title 23, U.S.C., requirements and generally applicable FHWA regulations also may be involved. For more information, see http://www.fhwa.dot.gov/ipd/p3/tools_programs/sep15.htm.

- **The TAP** (see, e.g., http://www.fhwa.dot.gov/map21/guidance/guidetap.cfm) provides funding for programs and projects defined as
  - Transportation alternatives on- and off-road pedestrian and bicycle facilities.
  - Infrastructure projects for improving non-driver access to public transportation and enhanced mobility.
  - Community improvement activities, and environmental mitigation.
  - Recreational trail program projects.
  - Safe route to school projects.
  - Projects for planning, designing, or constructing boulevards and other roadways largely in the right-of-way of former Interstate System routes or other divided highways.

4.8 Operational Objectives and Policies

As agencies begin the planning process for new price-managed facilities, they must make many important operational and policy decisions.

4.8.1 Establishing Operational Objectives

Establishing goals and objectives is an essential early step in the planning process for price-managed facilities. The establishment of operational objectives should also be a collaborative process between the project sponsor, the local MPO, transit partners and local communities.

Operating agencies are typically involved in the regional transportation planning process and interact with MPOs. However, it is important to engage day-to-day operating agency managers from a systems operations perspective and not simply as advocates for capital projects. Developing an interagency committee that focuses on improving regional management and operations has been an effective technique used by several MPOs to engage operators in addressing regional operations. This forum can be used to determine system performance priorities, operations objectives, data availability, and funding opportunities.

Once the goals for managed facility projects have been established, project sponsors and planning organizations develop a set of objectives to assess and compare the extent to which different pricing alternatives are able to achieve the desired goals. Possible objectives include one or more of the following:

- Improving travel-time reliability
- Maximum overall travel-time savings
- Maintaining minimum speed levels on the managed facilities
- Maximum vehicle throughput subject to traffic level of service or minimum speed constraints
- Maximum person throughput subject to traffic level of service or minimum speed constraints
- Maximize revenue

When the private sector is responsible for developing and financing price-managed facilities, their main objective may be to maximize revenue levels. However, public agencies implementing price-managed facilities may be more focused on maximizing operational efficiencies such as throughput and travel-time savings. These objectives need not be conflicting because revenue maximization should generally coincide with the optimization of operational efficiencies, such as throughput and travel-time savings.

4.8.2 Establishing Operational Policies

Operational polices including occupancy rates, hours of operations, and tolling schemes are also essential for managed facility projects. For example,

- Occupancy requirements: Most HOV and HOT facilities have 2+ occupancy requirement for free trips, but many facilities require 3+ instead. In general, decisions on occupancy rate should be driven by HOV utilization, revenue generation goals, and occupancy requirements on other managed facilities in the region. They may also reflect other regional goals such as encouraging transit ridership and ride-sharing.

- Vehicle requirements: Some facilities do not require an ETC transponder on HOVs that are eligible to use the facility for free and some do.

- Allowing free facility-usage for other types of vehicles: Often, inherently low-emission vehicles (ILEVs) can used price-managed facilities for free.

- The disposition of project revenues is of particular interest to the public. Decisions on the use of toll proceeds are often sensitive, affect public opinion, and should be addressed early. Close coordination with transit providers and using project's proceeds to support transit improvements is an effective strategy to gain support from stakeholders.

- Traffic and Revenue Forecasting: Planners must forecast demand levels for, e.g., both high-occupant and single-occupant vehicles that buy in under a variety of pricing and occupancy requirement scenarios. This exercise serves a dual purpose: First, it allows the project sponsor to determine the combination of pricing and occupancy requirements that maximizes transportation benefits for all motorists traveling in the price-managed facility corridor.

Second, it allows the project sponsor to forecast revenue streams and then evaluate financing approaches. Desirable characteristics for a travel-demand model include relevant travel choices (such as departure or arrival time, route, and mode choice), travel costs, willingness-to-pay, value of time, and value of travel-time reliability.

4.9 Pre- and Post-Implementation Performance

The evaluation of managed-facility operations should be conducted for a variety of reasons. Before-and-after studies determine whether the anticipated benefits outlined in the region's and corridor's goals and objectives are achieved. Ongoing monitoring and periodic evaluations ensure that the project provides the desired results. Monitoring and evaluations also identify when changes or enhancements in design or operation policies are necessary. Information on vehicle volumes, travel times, occupancy trends, transit patronage, violation rates and crash data are critical to an efficient and operationally sound project.

The evaluation process begins with setting measures of effectiveness that mirror goals and objectives. The following table provides some example measures that mirror common goals and objectives. Desirable threshold levels of change should be identified and will be used to determine whether the project has met the specified objective.

TABLE 4.2 Objectives and Related Measures of Effectiveness

Objective	Measure of Effectiveness
Improve Mobility	• Average speeds • Person or vehicular throughput • Average travel times • Rates of violation
Increase Reliability	• Speed or travel-time variation • Transit "on time" performance • Incident clearance times
Improve Safety	• Number of incidents by type • Incident response times
Decrease Environmental Impacts	• Vehicle miles traveled • Fuel consumption • Quantities of exhaust pollutants
Preservation of Revenue	• Gross and net revenue generation • Operations costs • Revenue leakage • Refunds for customer service • Refunds for diversion into managed lanes

Monitoring equipment includes systems to collect and process the necessary data to assess price-managed facility performance. At a minimum, roadway detection devices must be capable of frequently and reliably collecting speed, volume, and throughout the project.

Operators and algorithms evaluate operating conditions on the facility based on speed and volume characteristics and determine whether the toll or other operating policies need to be modified to ensure optimal performance. For dynamically priced systems, the toll-setting algorithm uses real-time speed and volume data. Operators also look at speed and volume trends over a daily, weekly, or monthly basis to evaluate the performance of fixed by time-of-day pricing strategies.

There are varieties of technologies available to detect traffic conditions at specific points along the corridor. Data collection equipment should be chosen based on cost, accuracy, reliability, maintainability, and the ability to integrate technologies with existing equipment. Traffic monitoring equipment serves a critical function of alerting managed facility operators to the presence of traffic disruptions. Non-recurring traffic disruptions—such as debris on the roadway or collisions—may warrant a change in toll rates on dynamically priced systems, incident information on variable message signs, and in certain cases, temporary lane closure.

Traffic cameras also serve a critical toll operations role, by confirming that appropriate toll rates and other informational messages are correctly functioning and displayed on variable message signs. Monitoring equipment may also alert operators to the existence of recurring traffic disruptions (i.e., significant slowing at access points), which may warrant a different type of management response.

The level of roadway detection and monitoring capability on price-managed facilities may need to be more extensive than that found on other GP facilities and maintained at a high level of functional reliability. Functional requirements for the detection and monitoring system need to be defined and implemented as part of the ITS and tolling integration systems that support the operations of the price-managed facilities. The functionality and accuracy of monitoring equipment should be tested at regular intervals to ensure that reported data is reliable. This is particularly important for systems that incorporate dynamic pricing algorithms that rely on accurate traffic data to properly set the toll rates.

5 IDENTIFICATION OF EVALUATION TOOLS

Similar to any other transportation improvement project, whether and where to implement arterial managed lanes ultimately depend on the benefit-cost ratios they yield. While it is usually easier to evaluate the cost for deploying a managed lane strategy, assessing and quantifying its benefit is not straightforward. The benefit is often multifaceted and can be affected by many factors, such as the utilization of the managed lane, travel time saving and reliability improvement of the users, impacts on other vehicles on GP lanes, and environmental impacts. Fortunately, quite a few tools and methodologies exist in the literature, which may be of help to evaluate the performance of a managed lane strategy.

Below, these evaluation tools are categorized into three types, i.e., sketch planning, project planning and operational planning tools. All these tools can be used to analyze managed lane strategies but differ in various aspects such as modeling resolution, scale and accuracy, data need and time requirement. For example, a sketch planning tool may provide quick assessments and is inexpensive to use, but it cannot analyze a particular alternative in detail. On the other hand, an operational planning tool is more competent for a detailed analysis, but it is more expensive to use and requires much more input data.

For the remainder, Section 5.1 reviews evaluation tools in the literature Section 5.2 compares different types of tools and makes improvement recommendations.

5.1 Evaluation Tools

In this section, we review the tools useful in evaluating the performance of a managed lane strategy. As aforementioned, we classify these tools into three types and we introduce them one by one below.

5.1.1 Sketch Planning

Sketch planning tools analyze a large set of alternatives in a quick and broad-based manner to identify a small set of the most promising alternatives for further analysis. Alternatively, they can be applied to conduct a high-level macroscopic analysis of a transportation policy in a large region (Meyer and Miller, 2001).

A few sketch planning tools have been developed to analyze managed lane strategies on freeways and arterials. They include the following:

- The Spreadsheet Model for Induced Travel Estimation - Managed Lanes (SMITE-ML) (www.fhwa.dot.gov/steam/smiteml.htm)
- Sketch Planning for Road Use Charge Evaluation (SPRUCE) (DeCorla-Souza, 2004)
- Quick-HOV (Wellander et al., 1998)
- Modified Charles Rivers Associates technique (modified CRA) (Wellander et al., 1998)
- Spreadsheet Method for Arterial HOV Facilities (SMArtHOV) (Wellander et al., 1998)
- Model of Sustainability and Integrated Corridors (MOSAIC) (Zhang et al., 2013)
- Policy Options Evaluation Tool for Managed Lanes (POET-ML) (Smith et al., 2008)
- High-Occupancy Toll Strategic Analysis Rating Tool (HOT START) (Eisele et al., 2006).

TABLE 5.1 provides a summary of the tools listed above. Many adopt a similar methodology to estimate traffic demands on managed lanes. For example, SMITE-ML, SPRUCE and MOSAIC apply the pivot point logit model while the modified CRA model uses a multinomial logit model.

Among these tools, QUICK-HOV, modified CRA, SMArtHOV and MOSAIC are applicable to arterial managed lanes. Below we review MOSAIC, POET-ML, and HOT START due to the availability of detailed information of the tools. Although the latter two are not designed for evaluating arterial managed lanes, their modeling approaches are capable of doing so if the characteristics of arterial corridors, such as the impacts of intersection and bus stops, are properly considered.

TABLE 5.1 Summary of Sketch Planning Tools

Tool	Usage	Application	Input	Output
SMITE-ML	Evaluate impacts of typical freeway capacity expansion projects involving managed lanes	Washington, DC.	Total daily person trips; percent in peak periods; transit mode share; average bus, auto and carpool occupancy; freeway capacity per lane; number of restricted freeway lanes; total arterial capacity, etc.	Travel speed; delay; toll revenues; user and social benefits
SPRUCE	Estimate impacts of toll road projects	Virginia	Average daily traffic volume for freeway and arterials; travel time and cost changes; freeway capacity per lane; number of restricted freeway lanes; total arterial capacity, etc.	Travel demand; travel speed; delay; toll revenues; user and social benefits
Quick-HOV	Predict traffic demand of HOV lanes	Vancouver, Washington	Length of corridor; number of HOV and GP lanes; whether or not the barrier is used to separate HOV and GP lanes; HOV eligibility requirements; existing vehicle volumes and average vehicle occupancy; average speed on parallel facility; signal density; cycle length; green splits; estimate of HOV lane violators, etc.	Travel times for HOV and non-HOV travel times; the percentage of HOVs using HOV lanes
Modified CRA	Predict traffic demand for arterial HOV lanes	Vancouver, Washington	Total traffic volumes; volume of HOVs and buses; average load factor of buses; average trip travel times; number of current and proposed vehicle lanes; average speeds; capacities of HOV and GP lanes; HOV eligibility requirements; length of HOV lane	Traffic volume of HOV lanes in the opening year

TABLE 5.1, continued

SMArtHOV	Analyze impacts of arterial HOV treatments, including HOV lanes, queue jumps and transit signal priority	Arizona, Vancouver, Washington	Volume of HOVs; volume of through vehicles; volume of right-turning vehicles; volume of buses using the facility; cycle length; red time for each phase; average stopped delay; average load factor for buses	Transit and HOV delay savings
MOSAIC	Evaluate impacts of corridor improvement options, including HOV, HOT, ET, bus-only, truck-only lanes, etc.	Maryland	Length of corridor; number of managed and GP lanes; HOV eligibility requirements; toll price of HOT lanes; number of intersections, etc.	Travel time; travel speed; travel demand for each mode; intersection delay; energy consumption; pollution emissions; crash rates; noise, etc.
POET-ML	Explore impacts of potential alternative policies on existing HOV facilities, including changing the HOV eligibility requirement and conversion to HOT lane, etc.	-	Length of corridor; number of HOV and GP lanes; HOV eligibility requirement; existing vehicle volumes and average vehicle occupancy; average speed on parallel facility, etc.	Demands of GP and HOV/HOT lanes; speeds of GP and HOV/HOT lanes; levels of service of GP and HOV/HOT lanes; travel time savings; emissions; total revenue
HOT START	Assess whether a conversion of HOV to HOT is likely to succeed	Texas	Scores of various factors including HOV lane utilization and willingness to pay tolls, etc.	Overall score of a HOT project

5.1.1.1 MOSAIC

The MOSAIC spreadsheet, sponsored by the Maryland State Highway Administration, was developed to evaluate the sustainability of different corridor improvement options such as HOV, HOT, ET, and bus-only lanes. This model can be used for both freeway and arterial corridors. In the following, we introduce its application to arterial corridors. Our introduction is heavily based on Zhang et al. (2013).

In MOSAIC, a key step is to estimate the modal shift once a managed lane strategy is implemented. The shift is captured by the following pivot point logit model:

$$P_i' = \frac{P_i \times e_i^{\Delta U_i}}{\sum_{j=1}^{k} \left(P_j \times e_j^{\Delta U_j} \right)}$$

where:

$P_i{}'$: New share of using mode i;

P_i: Original share of using mode i;

ΔU_i: Change in the utility of mode i; and

k: The number of all available modes.

In the above, ΔU_i represents the utility change due to the changes in travel time and costs, i.e., $\Delta U_i = b_i \times \Delta TT_i + c_i \times \Delta Cost_i$, where ΔTT_i and $\Delta Cost_i$ represent the changes in travel time and cost, and b_i and c_i are the corresponding coefficients. The travel time is calculated by the flowing equation:

$$TT = \frac{L}{V} + nT_{wait}$$

where:

L: The length of the corridor;

V: The roadway travel speed in the corridor;

n: The number of intersections in the corridor, and

T_{wait}: Average intersection delay.

Both the roadway travel speed and intersection delay can be estimated according to TABLE 5.2 and TABLE **5.3**.

TABLE 5.2 Speed Estimation Based on Daily Traffic Volume per Lane

Congestion Level	Daily Traffic Volume per Lane	Speed Estimate Equation Peak Speed (mph)
Uncongested	<5500	35
Medium	5500-7000	33.58-(0.74*ADT/LANE)
Heavy	7000-8500	33.80-(0.77*ADT/LANE)
Severe	8500-10000	31.65-(0.51*ADT/LANE)
Extreme	>10000	32.57-(0.62*ADT/LANE)

Note: ADT: Average Daily Traffic, and the unit is thousand; and the lowest speed is 20 mph.
Source: Zhang et al. (2013)

TABLE 5.3 Traffic Control Delay at Intersections

Congestion Level	Daily Traffic Volume per Lane	Average Delay at Intersections (Seconds per vehicle)	
		Signalized Intersections	Unsignalized Intersections
Uncongested	<5500	10	10
Medium	5500-7000	20	15
Heavy	7000-8500	35	25
Severe	8500-10000	55	35
Extreme	>10000	80	50

Source: Zhang et al. (2013)

To illustrate the procedure for estimating modal shift, consider a scenario of building one new HOV lane in a corridor. For those not eligible to use the lane, such as SOVs and trucks, it is assumed there is no change in their travel times at the first iteration, i.e., $\Delta TT = 0$ and thus $\Delta U = 0$. For the other modes, such as HOVs and buses, their travel times can be estimated as previously described. Based on the estimates of utility changes at the first iteration, the mode shares can be recalculated and the resulting traffic demands of different modes are then used for travel time calculation. Such an iterative process continues until the traffic equilibrium across the HOV and GP lanes is achieved, e.g., the difference in travel times of GP lane at two consecutive iterations is within one minute.

With the new travel times, MOSAIC estimates the travel reliability as follows (Ramani et al., 2009):

$$Reliability\ Index = 2.189 \times (Travel\ Time\ Index - 1) - 1.799 \times (Travel\ Time\ Index - 1)^2$$

The travel time index in the above expression is the ratio of actual travel time and the free-flow travel time or travel time at posted speed limits.

MOSAIC also provides estimates of energy consumption and air pollutant emissions based on actual speeds, as shown in TABLE 5.4. For other estimates, such as crash rate and noise, readers can refer to Zhang et al. (2013).

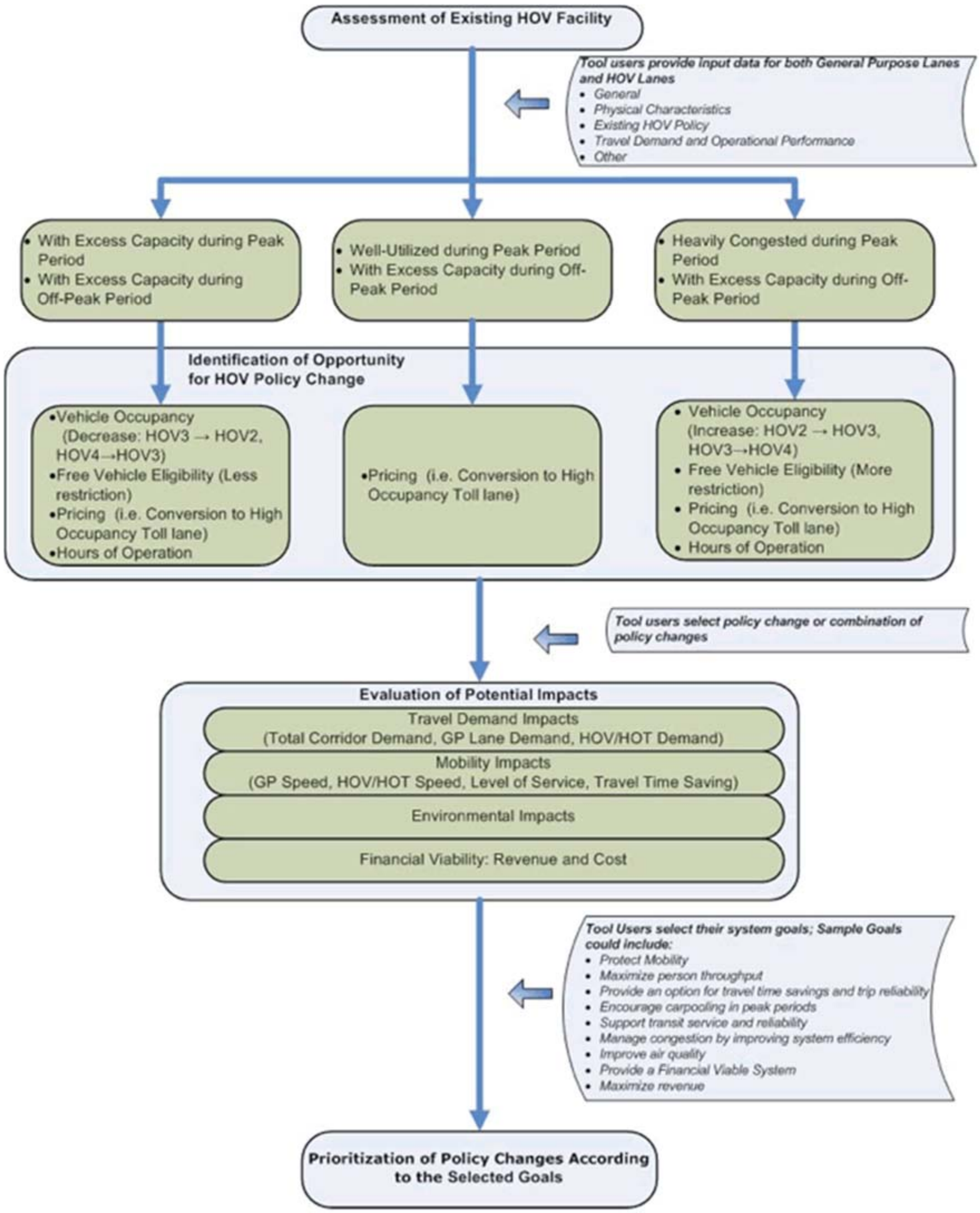
TABLE 5.4 Roadway Consumption and Emissions Rates

Speed (mph)	Energy Consumption per Vehicle (million BTU/mile)	CO (grams/mile)	NOx (grams/mile)	PM10 (grams/mile)
2.50	15.39	15.39	3.61	0.14
5.00	9.32	9.32	2.12	0.08
10.00	6.34	6.34	1.47	0.05
15.00	5.37	5.37	1.30	0.04
20.00	4.73	4.73	1.19	0.04
25.00	4.02	4.02	1.11	0.03
30.00	3.74	3.74	1.03	0.03
35.00	3.41	3.41	0.96	0.03
40.00	3.16	3.16	0.94	0.02
45.00	3.00	3.00	0.93	0.02
50.00	2.94	2.94	0.93	0.02
55.00	2.94	2.94	0.92	0.02
60.00	2.99	2.99	0.93	0.02
65.00	3.13	3.13	0.97	0.02
70.00	3.43	3.43	1.03	0.02
75.00	4.30	4.30	1.08	0.02

Source: Zhang et al. (2013)

5.1.1.2 POET-ML

POET-ML is a sketch planning tool that quantifies the impacts of potential alternative policies on existing HOV facilities. FIGURE 5.1 outlines the analytical process of POET-ML.



Source: Smith et al. (2008)

FIGURE 5.1 POET-ML Framework

The first step in the procedure is to assess the operational performance of existing HOV facility and classify them into one of the following three conditions: with excess capacity during both peak and off-peak periods; well-utilized during the peak period, but has excess capacity during the off-peak period or heavily congested during the peak period, but has excess capacity during the off-peak period. Various policy changes have been proposed for each condition. For example, if a HOV facility has excess capacity during both peak and off-peak periods, it is necessary to consider relaxing the occupancy and eligibility requirement or converting the facility into a HOT facility.

For each policy change, the second step is to evaluate its impacts on travel demand, mobility and environment, and its financial viability. Travel modes considered in POET-ML include carpool, transit, motorcycles, special fuel vehicle, taxi, and paying vehicles if HOT lanes are of interest. POET-ML makes ad hoc assumptions to estimate mode shares. For example, when converting HOV to HOT, traffic demand at a HOT lane is assumed to be maintained at least at LOS C (about 75% of capacity by default) during the peak period and no higher than the demand of GP lanes. The volume of paying vehicles is assumed to be equal to the spare capacity of the HOT lane. Moreover, these paying vehicles are assumed to come from both the GP lanes and parallel facilities with pre-specified splits, e.g., 30/70 split between GP lanes and parallel facilities when the GP lanes operate at LOS A while 40/60 split if the GP lanes operate at LOS B.

With the estimated demands, mobility impacts, such as travel speed, travel time, level of service are consequently calculated. Specifically, the following BPR function is adopted to estimate travel time:

$$T = T_f \times \left(1 + 0.9 \times \left(\frac{v}{c}\right)^3\right)$$

where T_f is the free-flow travel time (based on a speed of 65 mph); v represents traffic volume per lane per hour; and c is the lane capacity.

Using an average fuel consumption rate of 0.68 gallon per hour, POET-ML subsequently estimates the fuel consumption based on estimated travel times. Multiplying the fuel consumption with emission factors in TABLE 5.5 yields the emissions of CO, NO_x, and VOC. Similarly, with a minimum value of time of \$0.42 per min, POET-ML coverts total travel time saving of paying vehicles on the HOT lane into the toll revenue of the lane. Consequently, the financial viability of the facility can be assessed.

TABLE 5.5 Emission Factors

Air Quality - Pollutant	Passenger Car Emission Factor
CO (kg/gallon)	14.44
NOx (kg/gallon)	1.27
VOC (kg/gallon)	1.91
Carbon Dioxide (kg/gallon)	8.79

Source: Smith et al. (2008)

5.1.1.3 HOT START

HOT START was developed by Texas Transportation Institute, sponsored by the Texas Department of Transportation (Eisele et al., 2006). It is intended for evaluating the benefits of adapting an HOV lane to a HOT lane.

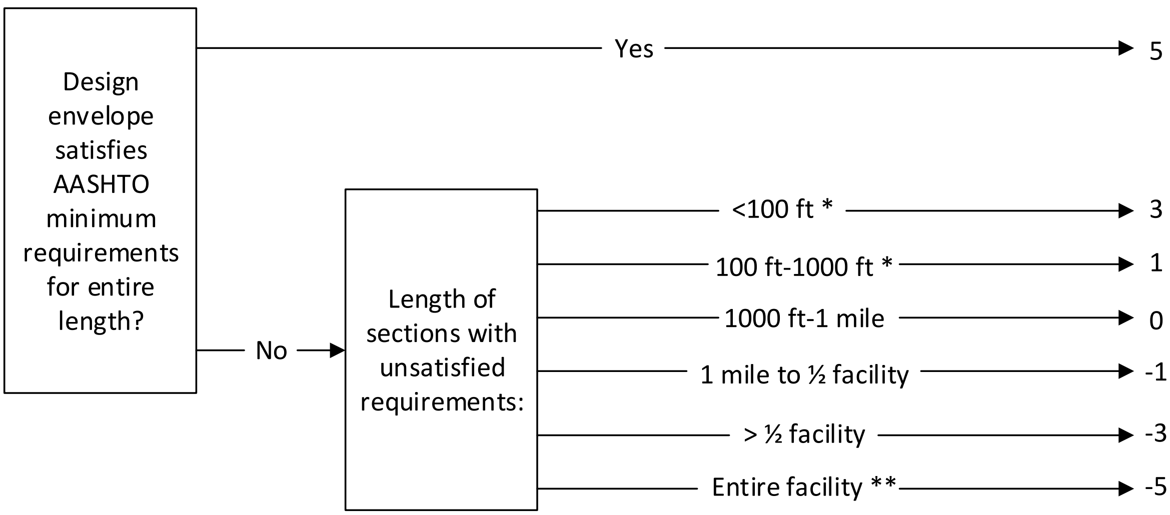
Instead of quantifying specific benefits, HOT START assesses the adaptation of an HOV lane to a HOT lane from scoring decision trees for key factors including lane separation for toll collection, facility access satisfying O-D requirements, access design, HOV lane utilization, travel time savings or reliability, public acceptance, political acceptance and so on. These factors are grouped into three categories, i.e., facility considerations, performance considerations, and institutional considerations (see TABLE 5.6). Moreover, to encapsulate these related factors into a comprehensive, logical and explainable analysis, each factor will be considered from three dimensions: weight, score, and interaction. Weight refers to the factor's significance relative to the goals of adaptation; score shows how well the factor is when compared with a desirable or minimum standard; interaction illustrates how much the factor is related to the other factors. The default weight of each factor is shown in TABLE 5.6.

TABLE 5.6 Factors When Considering Adaptation of HOV to HOT Lane

Categories	Factors	Default Weight
Facility factors	Facility cross section	6
	Lane separation for toll collection	6
	Facility access satisfies O-D requirements	5
	Facility access design	5
	Ability to enforce	5
	Facility traffic control	5
	Pricing strategy	5
	Incident management	3
	Maintenance	2
Performance factors	HOV lane utilization	6
	Travel time savings/ reliability	6
	Public agency/societal benefit	5
	Willingness to pay tolls	4
	Safety	4
	Environment	2
Institutional factors	Public acceptance Political	6
	Political acceptance	6
	Environmental justice/Title VI issues	6
	Revenue use	5
	Interagency cooperation	4
	Media relations	2
	Sustained public education/information	2

Source: Eisele et al. (2006)

Given the weight of each factor, a scoring method is proposed. The highest score of each factor is 5, while the lowest score is -5. FIGURE 5.2 illustrates the decision tree for the cross-section factor, in which *the Guide for High-Occupancy Vehicle Facilities* issued by AASHTO is referenced.



* Sections must be at least 1 mile apart.

** This is a critical issue and upon scoring is noted in the Results

Source: Eisele et al. (2006)

FIGURE 5.2 Sample Scoring Decision Tree for the Facility Cross-Section Factor

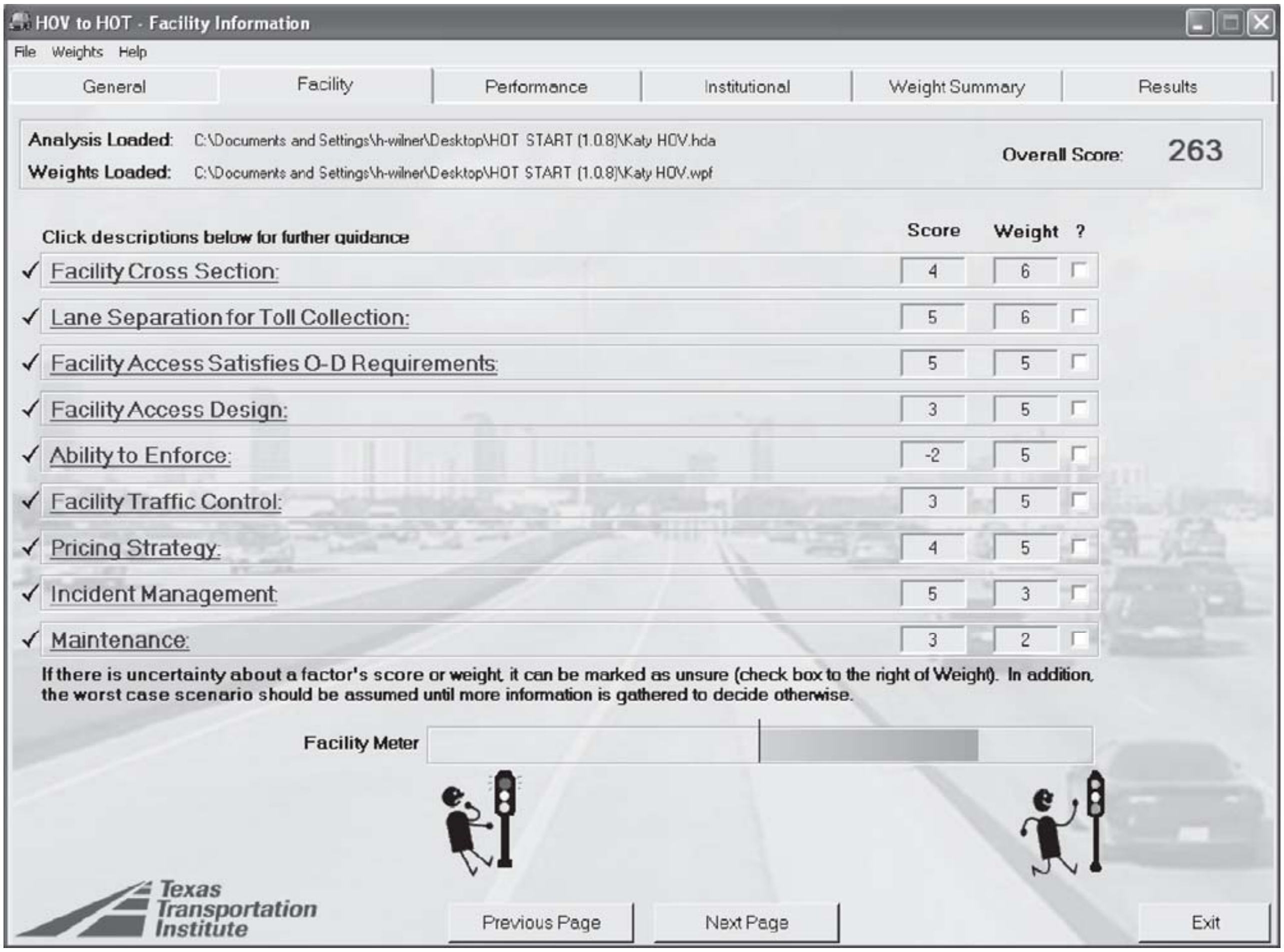
With the performance of each factor, it is also necessary to investigate the interactions between different factors. For example, a poor facility cross section factor will have negative impacts on the performance factors, such as decreasing the HOV lane utilization and increasing the travel time. Therefore, HOT START identifies the intersections of between the facility and performance factors as per TABLE 5.7.

TABLE 5.7 Interaction of Factors Affecting Adaptation of HOV Lane to HOT Lane

Facility Factor	**Performance Factor**					
	HOV Lane Utilization	Travel Time	Willingness to Pay Tolls	Safety	Environment	Benefits
Cross section	1	3	2	1		When any of the first five performance factors are impacted the benefits of the HOT lane are impacted
Lane separation		2		1		
Facility access for HOT O-D	3		2			
Facility access design		2	2	1		
Ability to enforce			3	3		
Facility signage	2		2	3		
Pricing strategy	1		1			
Incident management	3	3	2	3	3	
Maintenance	3	3	3	3		

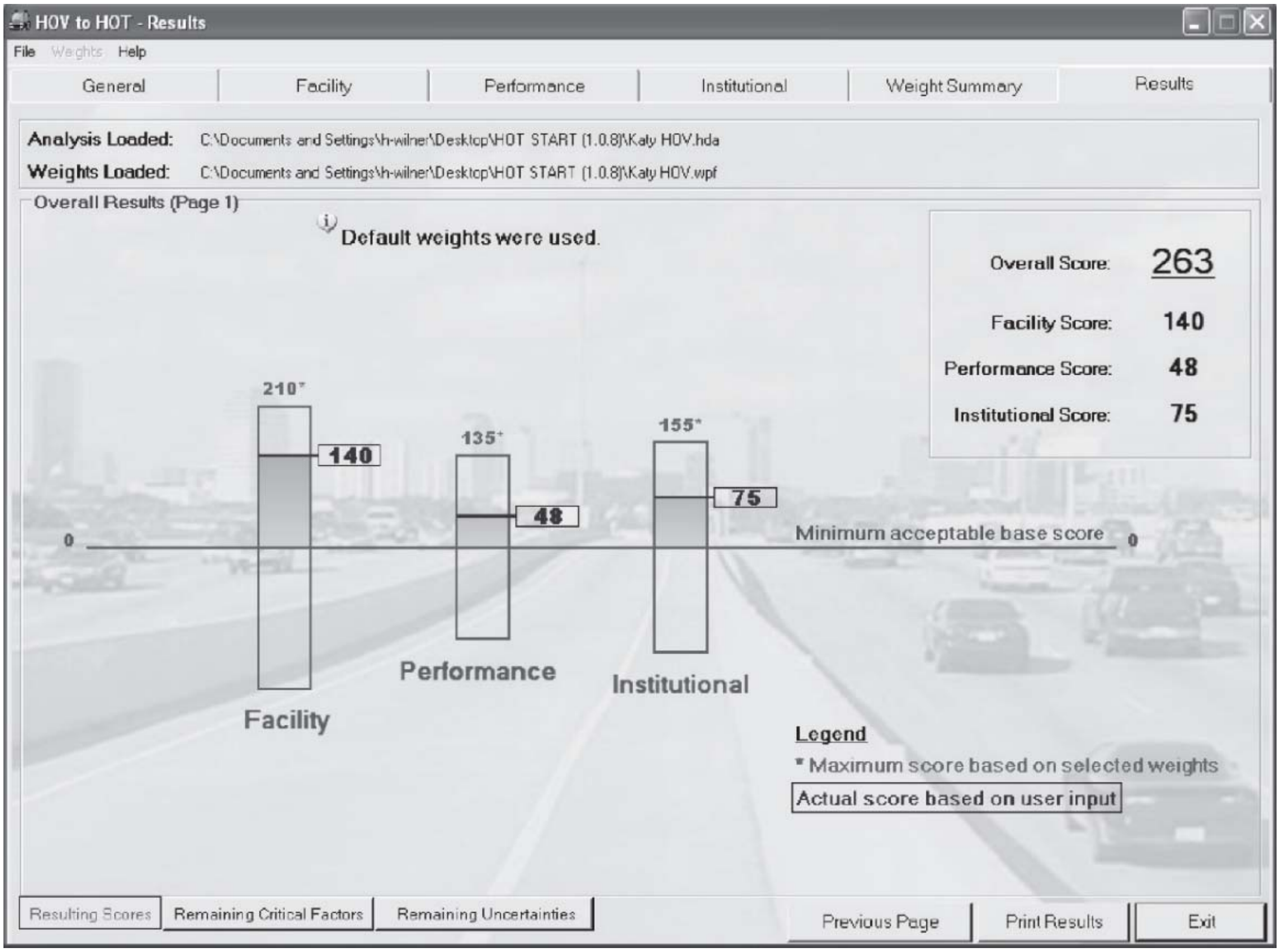
In the table, 1 = strong interaction, 2 = moderate interaction, and 3 = weak, but significant interaction
Source: Eisele et al. (2006)

The output of the above procedure includes the scores for various factors. Taking I-10 (Katy Freeway) HOV lane as an example, the scores of different facility factors are shown in FIGURE 5.3 while the final scores page is shown in FIGURE 5.4.



Source: Eisele et al. (2006)

FIGURE 5.3 I-10 HOV Facility Factors Scores



Source: Eisele et al. (2006)

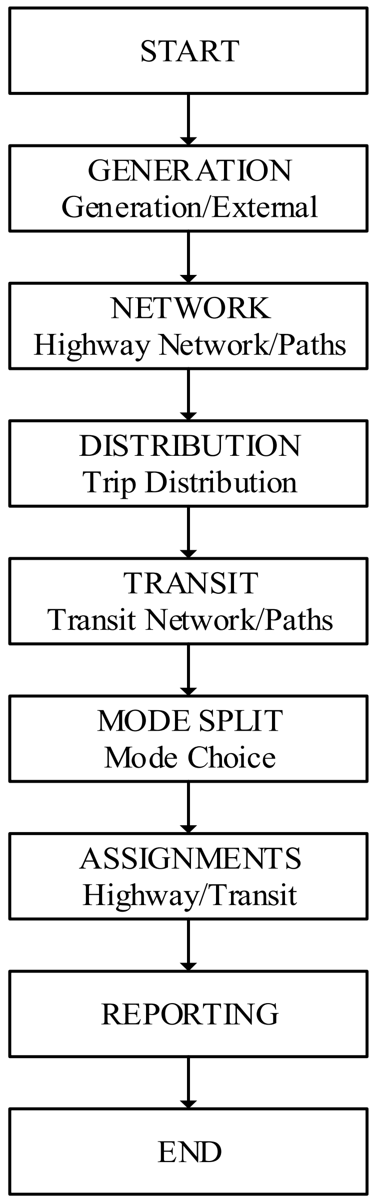
FIGURE 5.4 I-10 HOV Resulting Scores Page

5.1.2 Project Planning

Compared with sketch planning tools, project planning tools are more sophisticated for better capture the characteristics of travel demand and supply and their interactions. These tools primarily adopt the traditional four-step transportation planning process as the general methodology, with a limited number of them are activity based.

Below we describe the modeling of arterial managed lanes in the Florida Standard Urban Transportation Model Structure (FSUTMS) or FSUTMS modeling environment. It was developed by the FDOT for producing long-range travel demand forecasts throughout Florida. FSUTMS consists of a standardized set of modeling steps, software programs, operating procedures and urban area data formats, which many planning models in Florida generally follow.

FIGURE 5.5 is a sketch of the transit and highway demand modeling processes in FSUTMS. Note that trip assignments of transit and highway trips are separated. The impacts of bus-only lanes and the associated traffic management schemes such as queue jumps and transit signal priority can be reasonably captured in FSUTMS. Bus-only lane strategies lead to reductions in transit running times, which can be easily represented in transit assignment. Iterations between mode split and traffic/transit assignments are needed to capture the mode shift and the change in traffic conditions caused by the deployment of bus-only lane strategies.

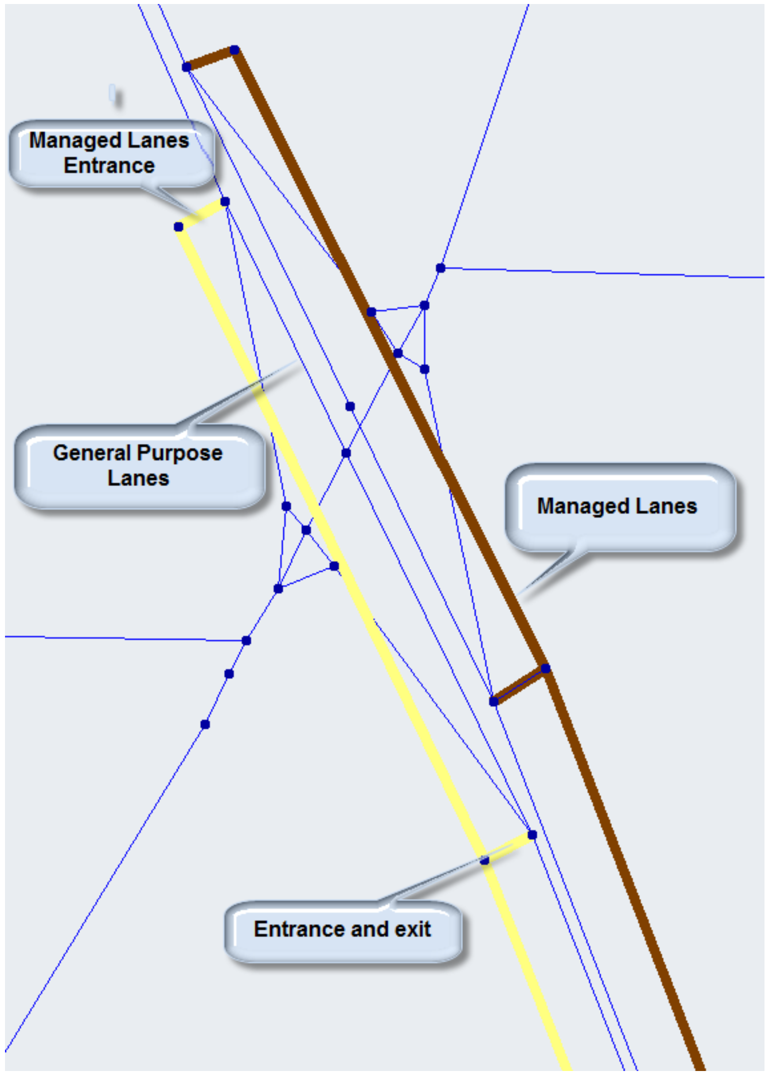


Source: FDOT (2012)

FIGURE 5.5 FSUTMS Transit and Highway Demand Modeling Processes

Because ET and HOV lanes can be treated as special cases of HOT lanes, below we only describe the modeling of HOT lanes in FSUTMS. Yin et al. (2007) summarize three procedures that have been applied or proposed to model HOT lanes in a traditional four-step modeling process. The first procedure is simplest and has been most often used to evaluate the impacts of converting HOV lanes into HOT lanes. In the procedure, auto trips on a tolled or non-tolled road are considered as distinct modes and a nested logit model and a subsequent loading process are applied to estimate the flows on HOT lanes. The primary advantage of using this procedure is that current mode choice models define utility functions for travel modes, which makes it convenient to include tolls as another variable in the functions. The primary drawback is that in the modeling process, iterations need to be performed until a stable equilibrium is reached such that travel times can be calculated and adopted in determining mode choice. In contrast to the first modal-split procedure, the second approach is deterministic or stochastic traffic assignment. The former coverts the toll into a time-equivalent, through VOT, and then incorporates it into volume-delay functions to assign trips among different paths. The latter uses a logit model to calculate the probability of using a tolled facility as a function of the relative cost/disutility between the tolled and non-tolled routes. The primary benefit of modeling toll roads in trip assignment is the ability to evaluate the influence of traffic congestion on demand for the toll facility. However, since different users have different VOTs, in order to be more accurate, multi-class trip assignment models need to be utilized. Another approach can be a post processor. It first calculates the market share of motorists who would use a toll facility under certain toll charge, and then uses a separate procedure to divert the calculated volume into toll lanes. Washington D.C. and San Diego, California used to apply this procedure. In the post processor, at least two alternative paths need to be developed: one using the toll route and the other using the best available non-toll route. Then the model uses diversion formulae to assign a percentage of the market to each route. Essentially, the post processor is a simplified stochastic loading procedure. The primary benefit is that the processor can be applied without modifying or recalibrating the existing four-step model while it may only capture part of the impacts that pricing may impose.

As indicated in Yin et al. (2007), the modal-split and traffic-assignment approaches are generally applicable to model HOT lanes in FSUTMS. As aforementioned, both approaches have pros and cons, but the trip-assignment approach may be more preferable. In the modal-split approach, the paths shared by both toll lanes and GP lanes generally lead to an incorrect estimation of modal splits because of the independence from irrelevant alternative property of the multinomial logit model. This is difficult to resolve in the current modeling framework. Further, iterations need to be performed until a consistency or equilibration is reached for the travel times used in mode choice and those resulted in trip assignment respectively. Such iteration is time consuming and the consistency may never be reached. For the trip-assignment approach, a multiclass stochastic user equilibrium assignment model is preferred where different VOTs may be used for classes with different trip purposes and income. FIGURE 5.6 shows the representation of HOT lanes in network coding for the traffic-assignment approach while TABLE 5.8 presents VOTs for different trip purposes in Southeast Florida.



Source: Parsons Brinckerhoff (2012)

FIGURE 5.6 Coding HOT Lanes

TABLE 5.8 Southeast Florida Travel Time Values by Travel Demand Model Trip Purpose

Market	Value (2004 Dollars)
Home-Based Work	$12.69 per hour
Home-Based Shopping	$10.59 per hour
Home-Based School	$10.58 per hour
Home-Based Social/Recreational	$10.59 per hour
Home-Based Other	$12.10 per hour
Home-Based Unknown	$11.34 per hour
Non-Home-Based	$12.10 per hour

Source: Corradino Group, Inc., and Cambridge Systematics, Inc. (2009)

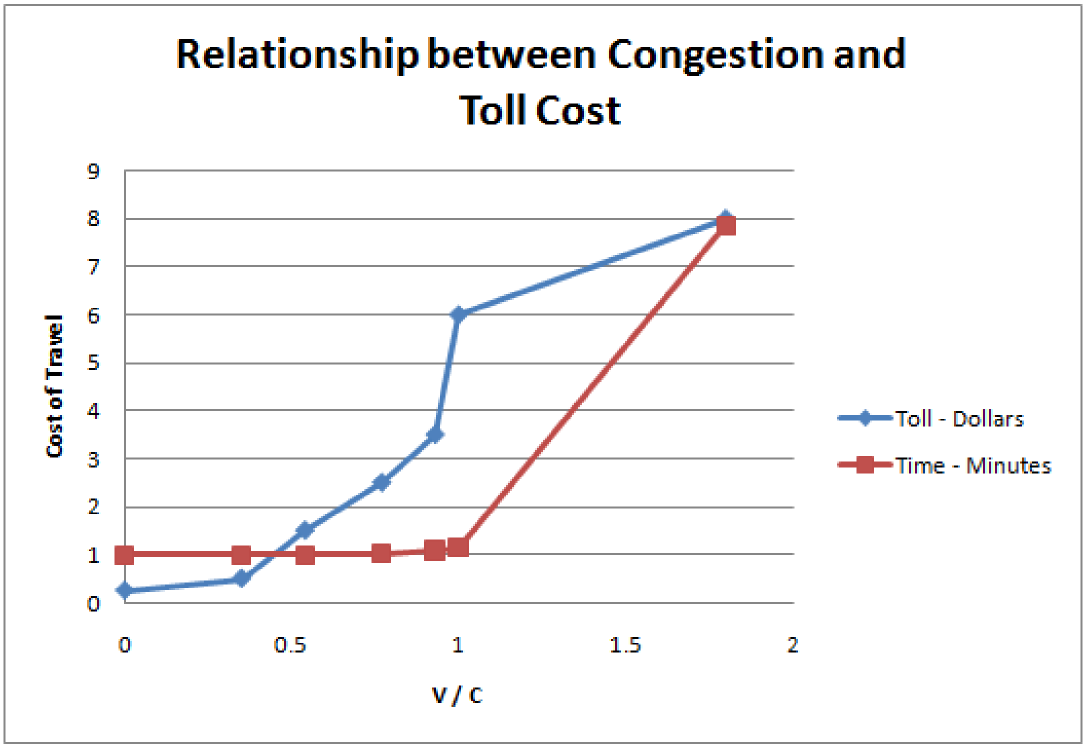
Recently, a HOT lane modeling approach in Parsons Brinckerhoff (2012) can be viewed as a combined mode split/traffic assignment procedure. The "mode split" is reflected by TABLE 5.9. At each iteration of the assignment procedure and for each origin-destination (O-D) pair, the travel time difference between vehicles using any segment of managed lanes and those without accessing managed lane are calculated and compared to the total amount of toll paid. The ratio between the toll and travel time saving are examined against TABLE 5.9 to determine the proportion of the O-D demand not using managed lanes. The remaining portion may use the lanes if it is "preferable" in the assignment.

TABLE 5.9 Not-Willing to Pay Proportion for Cost per Time Saved, by Demand Category

Toll Cents per Minute Saved	Demand Category							
	1	2	3	4	5	6	7	8
0	5	5	5	5	5	5	5	5
8	50	50	50	50	50	50	50	50
10	60	60	60	60	60	60	60	60
16.3	75	75	75	75	75	75	75	75
20	81.7	81.7	81.7	81.7	81.7	81.7	81.7	81.7
23.7	85	85	85	85	85	85	85	85
31.4	90.5	90.5	90.5	90.5	90.5	90.5	90.5	90.5
41.7	95	95	95	95	95	95	95	95
51.8	96	96	96	96	96	96	96	96
58.3	98	98	98	98	98	98	98	98
66.7	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8

Demand Categories:
1 - urban & rural short
2 - Long-Distance Business
3 - Long-Distance Tourist
4 - Short, Cross-border EI
5 - Long-Distance US, Canada
6 - Medium Trucks
7 - Unused
8 - Light Trucks
Source: Parsons Brinckerhoff (2012)

In the procedure, the toll rate is congestion dependent in the procedure and varies according to a look-up table whose relationship is sketched in FIGURE 5.7. The procedure is simple to implement and flexible enough to reflect various considerations for different types of analysis. However, one of the challenges is to accurately determine the not-willing-to-pay proportions, which encapsulate other variables in addition to the values of travel time.



Source: Parsons Brinckerhoff (2012)

FIGURE 5.7 Congestion Level versus Toll

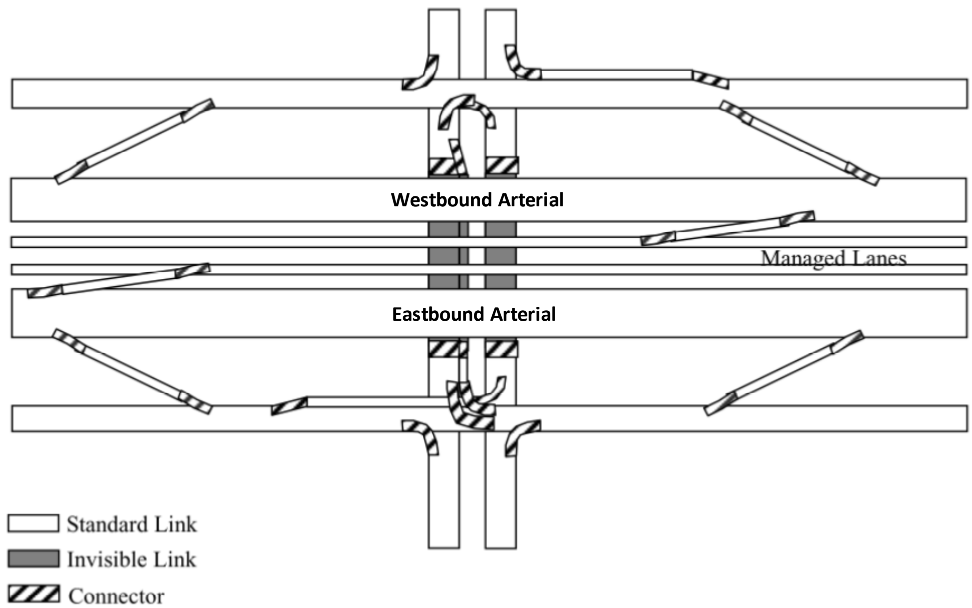
5.1.3 Operational Planning

The analysis based on either a sketch or project planning tool is not sufficient for supporting the design and operations of a managed lane facility. These tools do not adequately model traffic dynamics and fail to capture complex interactions among a large set of design and operations variables. Therefore, before a major investment deployment, it is often essential to use an operational planning tool to further evaluate different designs of managed lanes and traffic management schemes, e.g., where to locate ingress/egress points and queue jumps, how to time traffic signal and manage turning movements at intersections.

Often, operational planning tools are microscopic traffic simulators such as VISSIM, Paramics, CORSIM, and SimTraffic. Among them, some consider VISSIM as the most appropriate tool to model managed lanes (Fenno et al., 2002). On the other hand, a team at University of Florida has enhanced CORSIM and made it a tool particularly useful for simulating the operations of HOT lanes (Michalaka et al., 2012). Below we thus focus on VISSIM and CORSIM.

5.1.3.1 VISSIM

VISSIM is a software for microscopic traffic simulation developed by Planung Transport Verkehr AG (PTV). Similar to others, VISSIM provides a graphical user interface for network coding and allows users to use AutoCAD drawings and aerial photographs as background to help create a network. Unlike others that use a link-node structure, VISSIM implements a link-connector structure, where “links are used to represent roadways and are continuous (even through intersections), as long as the fundamental geometry (i.e., primarily, the number of lanes) remains constant. Where junctions and intersections occur, connectors are used to provide turning and/or merging/diverging vehicles with a path off of one link and onto another." (Fenno et al., 2002). See FIGURE 5.8 for an example. Signal controllers and stop, yield, speed control signs can be directly added to the network.

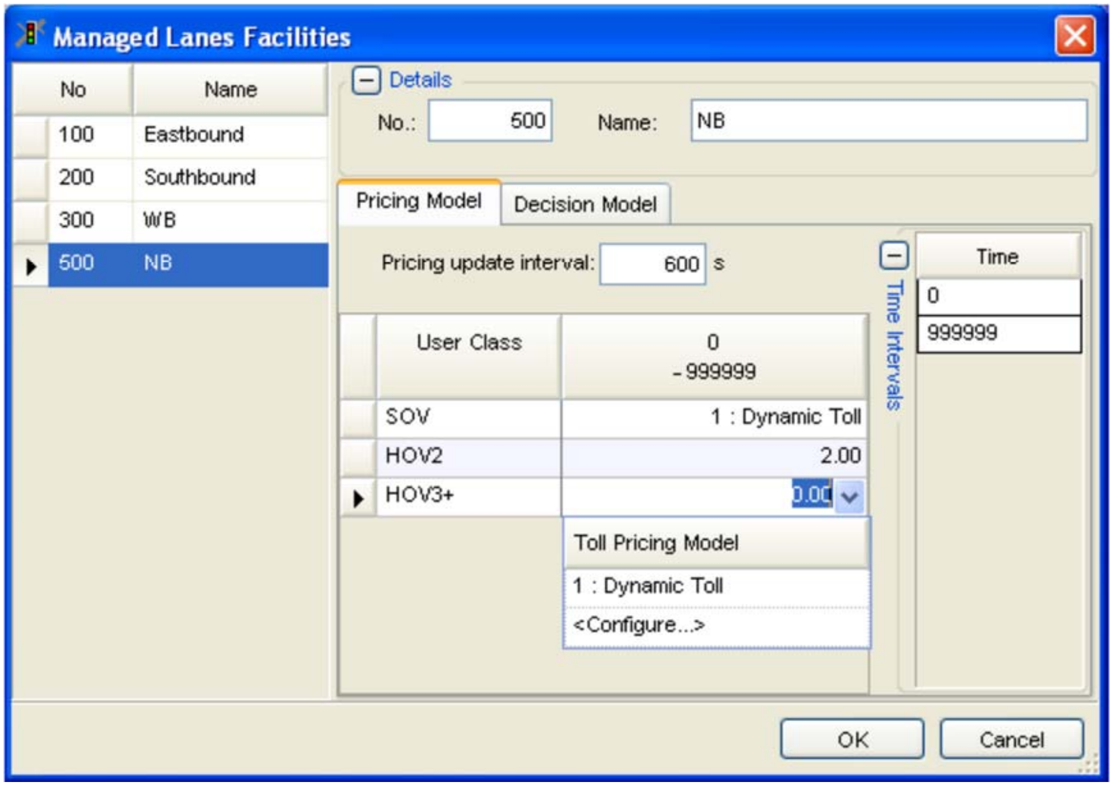


Reproduced by authors based on Fenno et al. (2002).

FIGURE 5.8 Geometric Elements of VISSIM Modeling

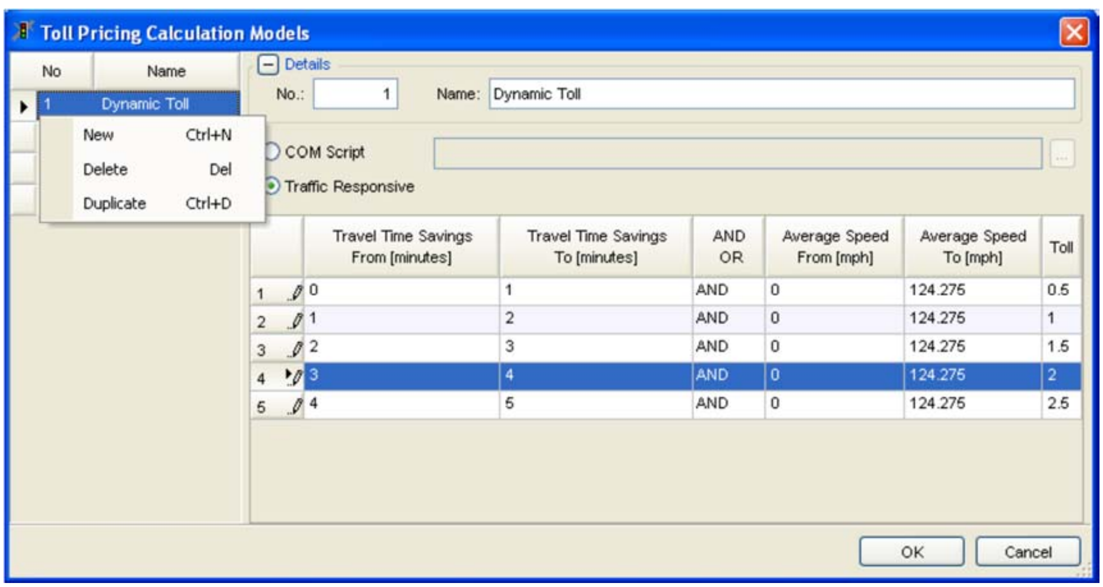
To model HOT, HOV and ET facilities, VISSIM provides a module called *Managed Lanes Facilities* (see FIGURE 5.9) for VSSIM users to edit their characteristic, such as tolls for different user classes. To model an HOV facility, the toll for ineligible classes can be set as very high in the *Pricing Model* (see FIGURE 5.9). For dynamic tolling, VISSIM considers a traffic-responsive scheme where the toll rate varies with respect to average speed in a pre-determined manner (see FIGURE 5.10).

To model drivers' lane choices, VISSIM uses a binary logit model, where the deterministic portion of the utility function consists of only two components, i.e., travel time and toll. FIGURE 5.11 shows the window where VISSIM users can input the parameters in the logit model, including the scale parameter and the coefficients associated time and toll.



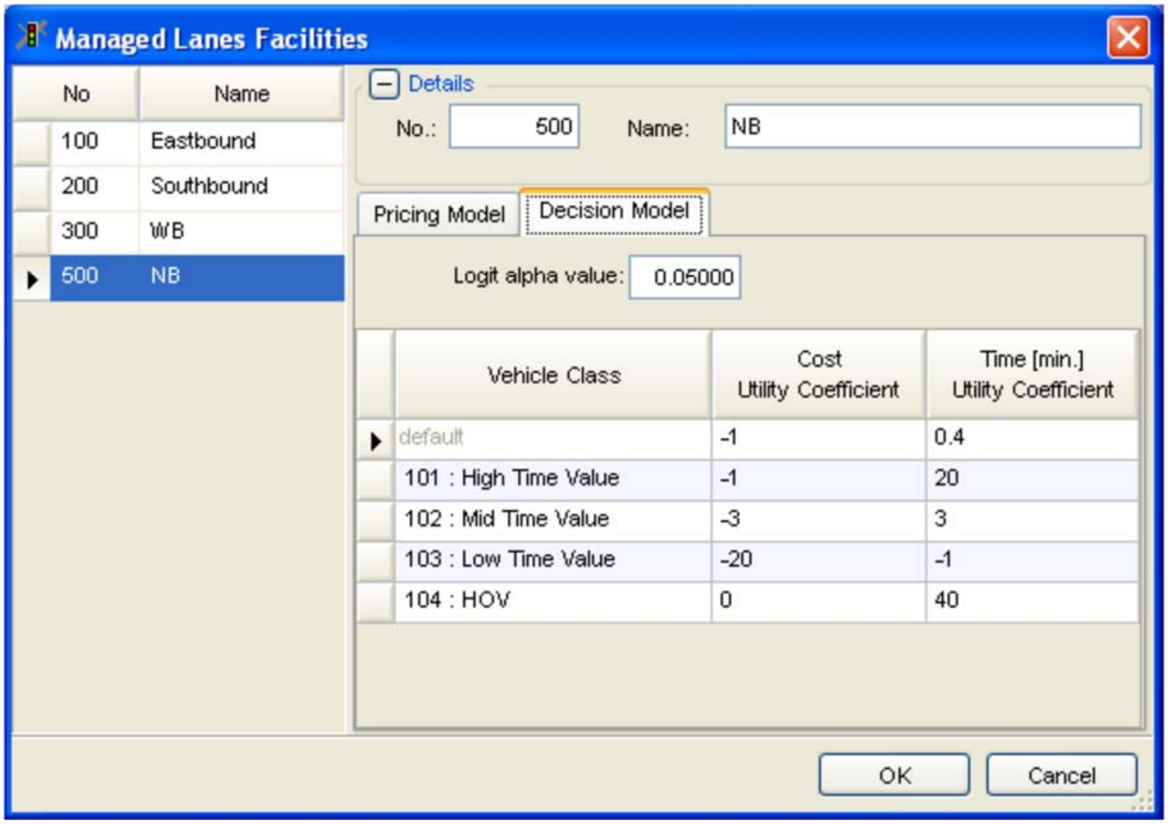
Source: PTV (2011)

FIGURE 5.9 Managed Lanes Facilities Window in VISSIM



Source: PTV (2011)

FIGURE 5.10 Toll Pricing Calculation Models

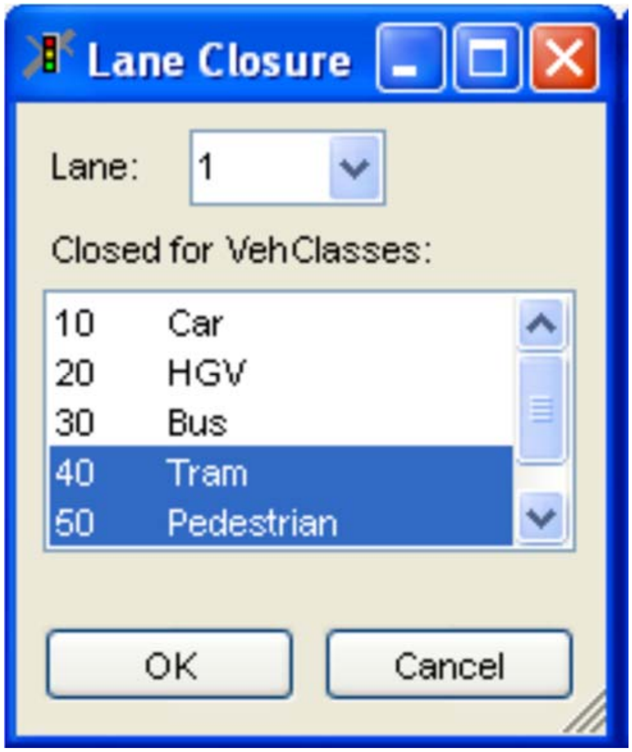


Source: PTV (2011)

FIGURE 5.11 Decision Model of Managed Lanes

To simulate bus-only lanes in VISSIM, it is possible to specify whether the lane at which the transit line runs is bus-only or not using the *Lane Closure* editor shown in FIGURE 5.12. If the lane is closed to other types of vehicles, it is a bus-only facility.

VISSIM is also capable of simulating a number of intersection treatments, such as transit signal priority and queue jumps. For example, a queue jump lane can be set to open only to certain types of vehicles via the *Lane Closure* editor. Then the *Signal Head* editor (see FIGURE 5.13) can be configured to provide early green to the vehicles in the queue jump lane.



Source: PTV (2011)

FIGURE 5.12 Lane Closure Editor

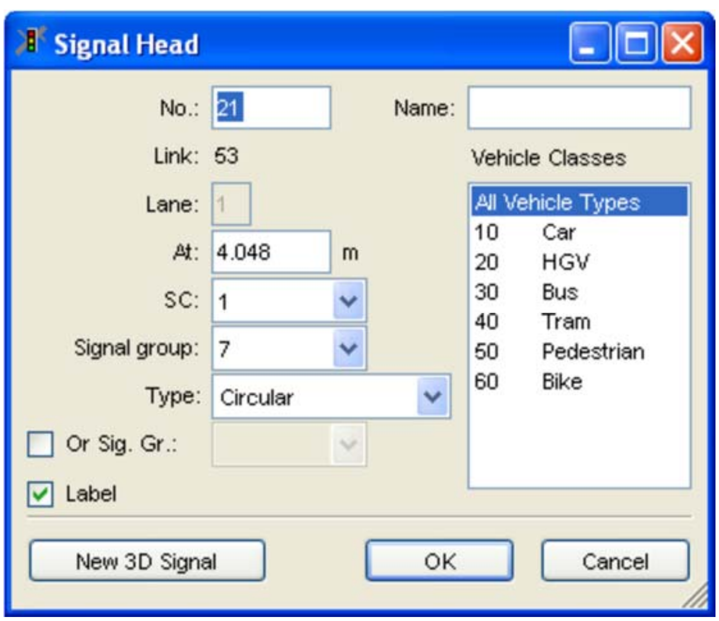


FIGURE 5.13 Signal Head (PTV, 2011)

5.1.3.2 CORSIM

CORSIM is a widely-used microscopic traffic simulation software, originally developed by FHWA. It is now maintained, developed and distributed by McTrans at the University of Florida. The tool is capable of simulating surface streets, freeways, and integrated networks with a complete selection of control devices.

The procedure of simulating bus-only lanes in CORSIM is very similar to VISSIM. Details about bus operations can be found in the CORSIM Reference Manual (Record Type 185-189), and bus lanes can be channelized for buses only (Record Type 11).

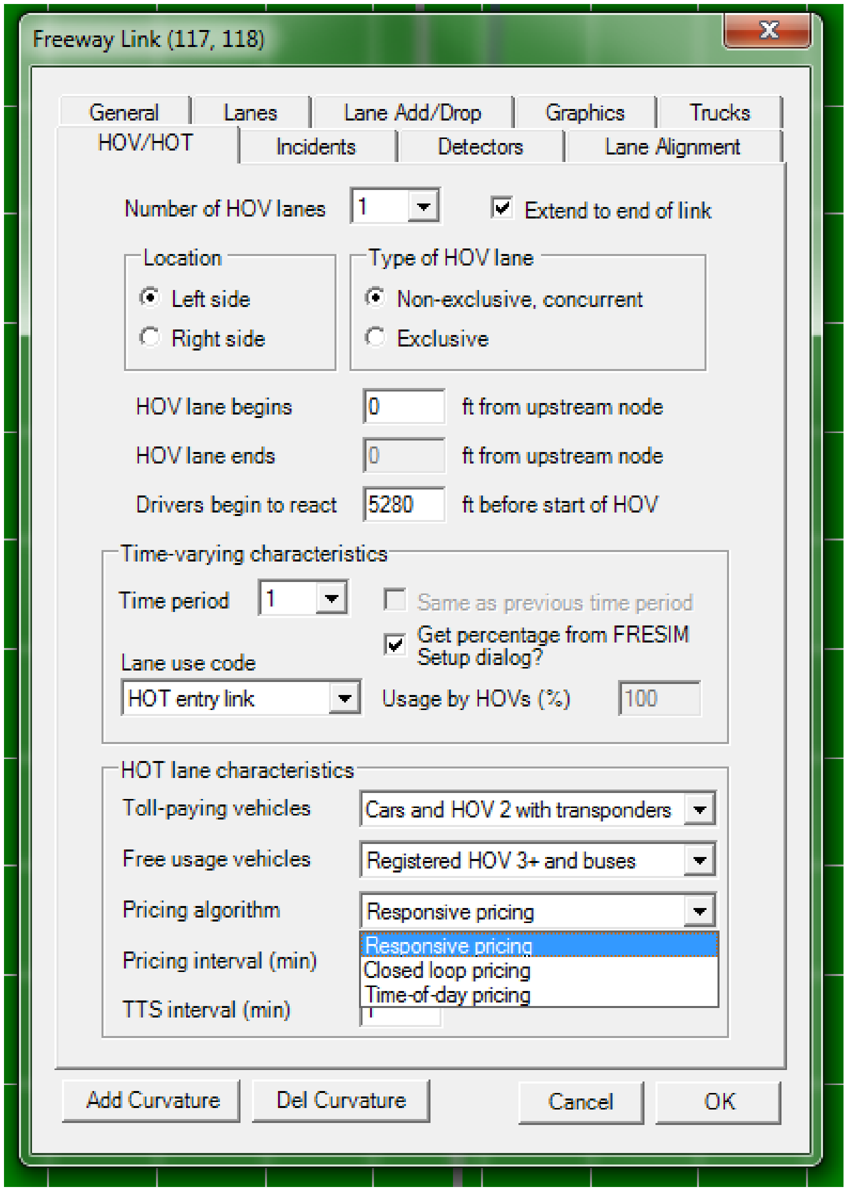
Recently, Michalaka et al. (2012) enhanced CORSIM's capability of simulating HOT lane operations. Three modules were developed, including dynamic tolling algorithms, toll structures for a HOT facility with multiple tolling segments, and modeling lane-choice behaviors of drivers between HOT and GP lanes.

Tolling algorithms

The enhanced CORSIM offers three types of pricing algorithms, including traffic responsive pricing, closed-loop control, and time-of-day pricing (see FIGURE 5.14). For the traffic responsive pricing, the traffic density (TD) in the current time interval and the difference between traffic densities in the current and previous time interval are used for determining the toll based on the Delta Settings Table shown in FIGURE 5.15. For closed-loop pricing, the traffic density in the current time interval and a pre-determined critical density (D_{cr}) are used for toll calculation as per the following equation:

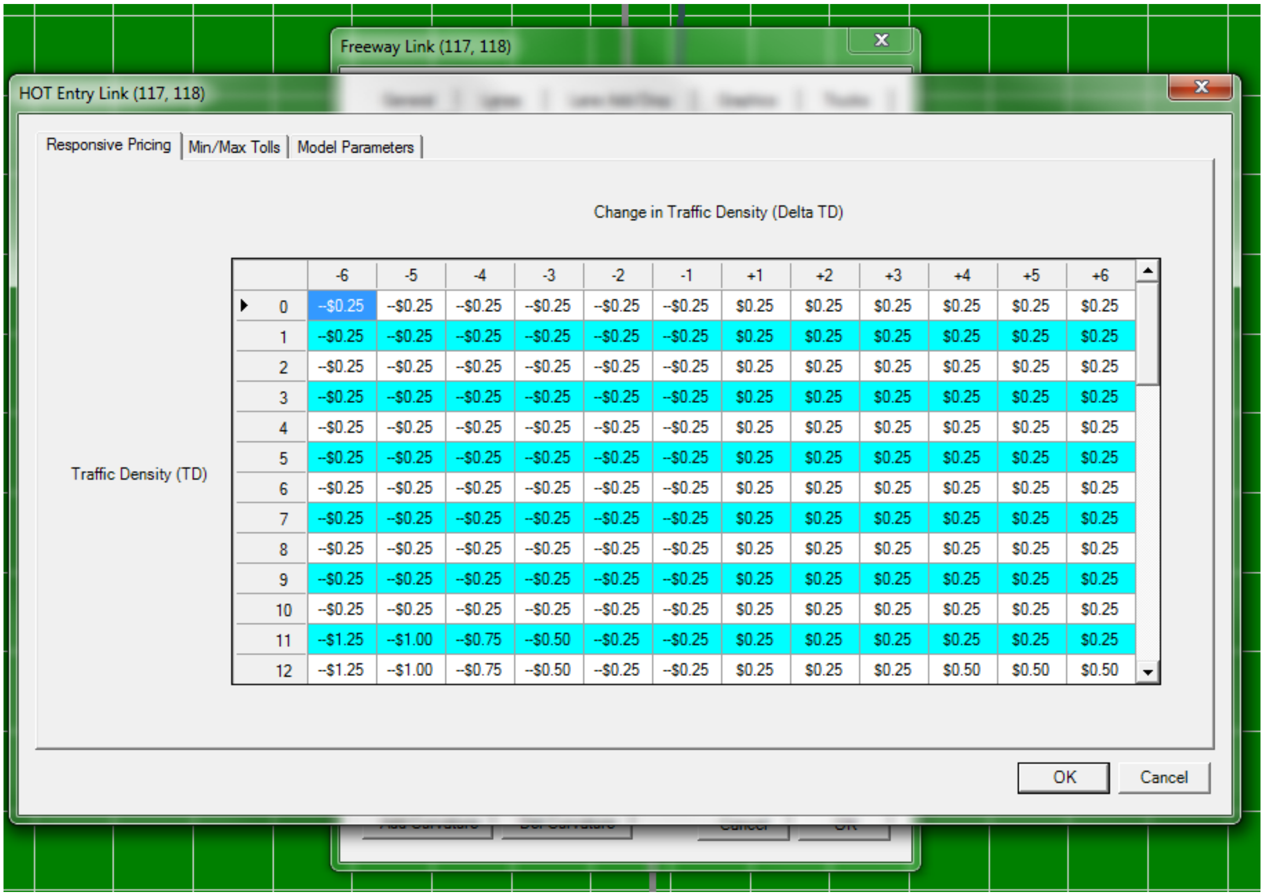
$$R(t+1) = R(t) + K \times (TD\ (t) - D_{cr})$$

For the above expression, $R(t)$ is the current toll amount; $R(t+1)$ is the toll amount for the next time interval; and K is a regulator parameter defined by the user. For time-of-day pricing, the toll varies by a toll schedule, which is pre-defined by users. The largest number of time intervals is 24, and the duration of each time interval can vary from 3 to 60 minutes.



Souce: **Michalaka et al. (2012)**

FIGURE 5.14 Pricing Algorithms Available in Enhanced CORSIM



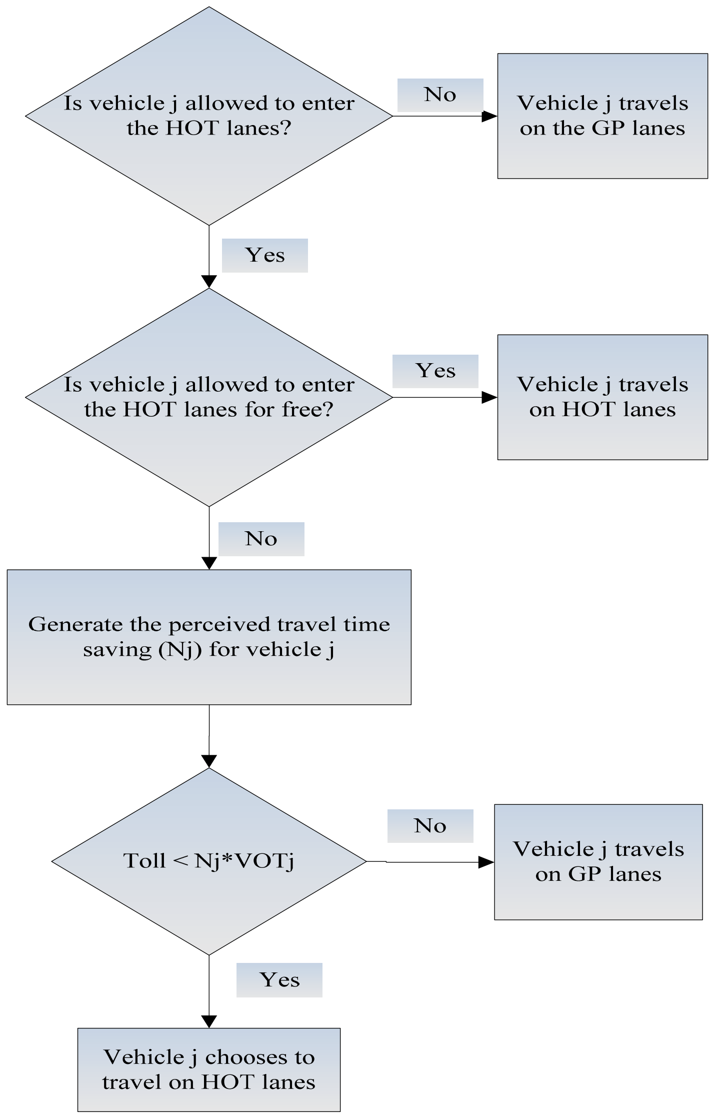
	-6	-5	-4	-3	-2	-1	+1	+2	+3	+4	+5	+6
0	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
1	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
2	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
3	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
4	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
5	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
6	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
7	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
8	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
9	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
10	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
11	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
12	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25	$0.25	$0.25	$0.25	$0.50	$0.50	$0.50

Source: Michalaka et al. (2012)

FIGURE 5.15 Delta Settings Table in Enhanced CORSIM

Lane choice

In the enhanced CORSIM, both the HOT and GP lanes are integrated as a single facility and the lane-choice behaviors are simulated endogenously. Considering that it is always costly for users to collect data to calibrate a sophisticated logit-type lane-choice model, CORSIM implements a simple decision rule, where motorists pay to use a HOT lane if the benefit they perceive from travel time saving is greater than the toll amount they are charged. The perceived benefit is the VOT of the traveler multiplying the perceived travel time saving, which is assumed to follow a truncated normal distribution whose mean is the real or actual travel time saving (RTTS) and standard deviation is specified by CORSIM users. The RTTS is the difference between the travel times on GP and HOT lanes, averaged across a user-specified time interval. Travelers' VOTs can be specified by CORSIM users as shown in TABLE 5.10. The lane choice procedure for a particular vehicle that is approaching a warning sign upstream to a HOT lane entrance is illustrated in FIGURE 5.16.



Source: Michalaka et al. (2012)

FIGURE 5.16 Drivers' Lane Choice in Enhanced CORSIM

TABLE 5.10 Value of Time ($/hr)

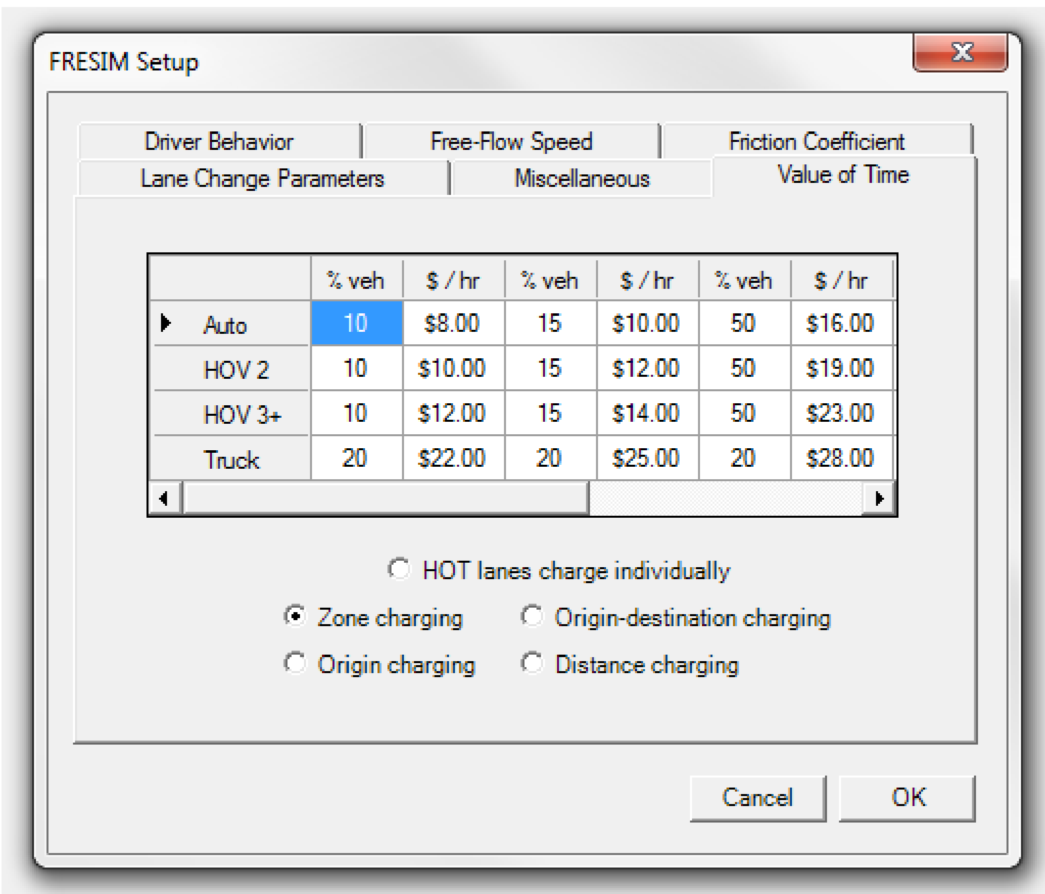
	% vehicles	VOT	% vehicles	VOT	% vehicles	VOT	% vehicles	VOT	% vehicles	VOT	Weighted Average
Cars	10	8	15	10	50	16	15	18	10	22	15.2
HOV 2	10	10	15	12	50	19	15	22	10	26	18.2
HOV 3+ not registered	10	12	15	14	50	23	15	26	10	31	21.8

Source: Michalaka et al. (2012)

Toll structures

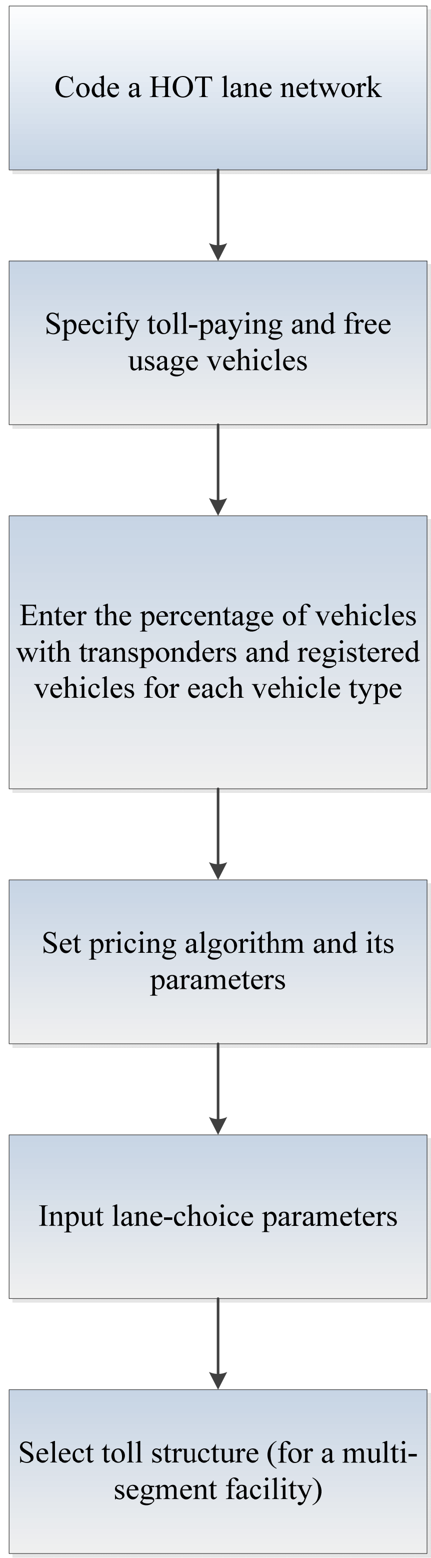
As discussed in the Section 3, there are four types of toll structures for a HOT facility with multiple tolling segments, including zone-based, origin-based, distance-based and origin-destination-based. CORSIM simulates all these four toll structures, in addition to the scenario of each HOT lane being a stand-alone single-segment facility and charged individually.

FIGURE 5.18 presents the steps of simulating HOT lanes in CORSIM. For details, please refer to Michalaka et al., (2012).



Source: Michalaka et al. (2012)

FIGURE 5.17 VOT and Toll Structure Editor in Enhanced CORSIM



Source: Michalaka et al. (2012)

FIGURE 5.18 Simulating HOT Lanes in Enhanced CORSIM

TABLE 5.11 describes outputs from CORSIM that include, e.g., average density, real travel time saving, revenue, and some input data such as pricing algorithm, minimum and maximum tolls defined by the user.

TABLE 5.11 CORSIM Output File

Column No	Column Name	Explanation
Inputs		
1	TIME	Simulation time when the toll is calculated and updated.
2	UPSTREAM NODE	Upstream node of the HOT entry link.
3	DOWNSTREAM NODE	Downstream node of the HOT entry link.
4	PRICING ALGORITHM	Pricing algorithm selected for toll calculation.
5	ORIGIN	Origin (applies only to OD-based tolling to be implemented).
6	DESTINATION	Destination (applies only to OD-based tolling to be implemented).
7	ZONE	Zone number (applies only to zone- and distance-based tolling).
8	MIN TOLL	Minimum toll set by the user (applies only to responsive and closed-loop-control-based pricing)
9	MAX TOLL	Maximum toll set by the user (applies only to responsive and closed-loop-control-based pricing)
Outputs		
10	DENSITY	Average density calculated over a zone or segment (applies only to responsive and closed-loop-control-based pricing)
11	DELTA DENSITY	Difference in density between two tolling intervals (applies only to responsive pricing)
12	PRICE	Toll amount
13	TOLL PER MILE	Toll rate, i.e., toll per mile (applies only to distance-based tolling)
14	MIN CHARGE	Minimum toll for entering the facility (applies only to distance-based tolling)
15	MAX CHARGE	Toll amount for traveling to the end of the facility (applies only to distance-based tolling)
16	RTTS	Real or actual travel time saving
17	REVENUE	Revenue
18	ZONE REVENUE	Revenue for each zone (applies only to zone and distance-based tolling)

Source: Michalaka et al. (2012)

5.2 Evaluation and Recommendation

Below is a summary of our evaluation along with our recommendation.

- Sketch Planning Tools: We identify several sketch planning tools useful in evaluating strategies for managed lanes on arterials. Some are limited to analyzing a particular type of strategies such as converting an HOV into a HOT lane while others are more comprehensive. All of them are intended to provide a quick and high-level assessment of a large set of alternatives. Among them, MOSAIC appears the most comprehensive and is capable of evaluating different types of corridor improvements including HOV, HOT, ET, and bus-only lanes. Its methodology is sound and reasonable. It thus holds the most promise for being applied to evaluate arterial managed lane strategies in Florida. Related parameters need to be recalibrated for conditions in Florida. Further enhancements are needed to better capture traffic delays at intersections with different types of intersection treatments and to consider the impacts of bicycles, pedestrians, and bus stops etc.

  Although SMArtHOV is not described in this report due to the lack of information, it has a reputation of being a good analysis tool for arterial HOV lanes, queue jumps, and transit signal priority systems (Wellander et al., 1998). Its applicability can be further investigated.

- Project Planning Tools: We review the capacity of FSUTMS in modeling arterial managed lane strategies. In general, FSUTMS can reasonably accommodate different managed lane strategies. FSUTMS contains elements that can cause a traditional four-step procedure to offer erroneous forecasts. However, these shortcomings are not unique to analysis of managed lane strategies. They also present when used in investigating, e.g., emerging policy issues and mobility options. Although activity-based models show promise for analyzing managed lane strategies in an integrated way, they are much more complex and require more resources to implement.

  For FSUTMS to better model arterial managed lane strategies, future research is needed to enhance link performance functions to capture the impacts of different intersection treatments, e.g., queue jumps, signal priority, turning movement management, on intersection delays and link travel times. Moreover, to adequately capture the impacts of bus-only lanes on other regular vehicles and more accurately predict the mode shift from highway to transit, a multimodal traffic assignment model can be applied in FSUTMS, which, however, substantially changes its transit modeling process.

- Operational Planning Tools: Existing operational planning tools are capable of conducting sophisticated analysis for various types and designs of arterial managed lane strategies. Among them, the enhanced CORSIM provides unique feature and functionality of simulating different types of toll lanes while VISSIM is a promising tool for simulating strategies related to bus-only lanes with advanced traffic signal control.

TABLE 5.2 summarizes the above findings.

TABLE 5.12 Summary of Recommended Tools

Tool	Usage	Recommendations
MOSAIC	Sketch planning for HOV, HOT, ET, bus-only and truck-only lanes etc.	Related parameters need to be calibrated to represent the prevailing conditions in Florida. Further enhancements are needed to better capture traffic delays at intersections with different types of intersection treatments, and consider the impacts of bicycles, pedestrians, and bus stops etc.
FSUTMS	Project planning for various types of managed lane strategies.	Future research is needed to enhance link performance functions to capture the impacts of different intersection treatments on intersection delays and link travel times. Moreover, to adequately capture the impacts of bus-only lanes on other regular vehicles and more accurately predict the mode shift from highway to transit, a multimodal traffic assignment model can be applied in FSUTMS.
VISSIM/CORSIM	Operations planning for various types of managed lane strategies.	The enhanced CORSIM provides unique functionality of simulating different types of toll lanes while VISSIM is a promising tool for simulating strategies related to bus-only lanes with advanced traffic signal control.

6 IMPACTS OF MANAGED LANES ON FREEWAYS AND ARTERIALS

This section discusses how to estimate or forecast the impacts of managed arterial lanes on average travel delay in a road network and demonstrate how these estimates can be used in identifying and coordinating deployments and operations of these lanes. More specifically, we describe two procedures, steepest decrease (SD) and pairwise interchange (PI) procedure. The SD procedure selects a pre-specified number of arterials for managed lane implementations and the other procedure (PI) evaluates a plan for managed lane deployment.

Both procedures rely on results from solving a multi-modal equilibrium problem with different inputs. The equilibrium problem is similar to one in Song et al. (2014). Below, Section 6.1 describes the road network for South Florida used in our case studies below. Sections 6.2 and 6.3 present the two procedures and illustrate them using the network in Section 6.1.

6.1 Network for Case Studies

To illustrate our approaches, we use the network of freeways and arterials in FIGURE 6.1. Only road segments highlighted in blue are included in our case studies. In FSUTMS, these freeways and arterials are of types listed in TABLE 6.1. For our case studies, those with codes 21, 41, and 61 are considered as arterials whose lanes can be managed to, e.g., reduce traffic congestion and improve mobility.

TABLE 6.1 Facility-Type Code for Freeways and Arterials

Facility-type Code	Explanation
11	Freeway Segments
12	Freeway Segments
21	Uninterrupted Segments
41	Higher Speed Interrupted Facility
61	Lower Speed Facility and Collector
81	2+ HOV Segments
91	Toll Freeway Segment

FIGURE 6.1 Arterials and Highways in South Florida

FIGURE 6.2 is a representation of the road network in FIGURE 6.1 used in our model. Generally, nodes in FIGURE 6.2 represent intersections or interchanges between several highways. However, some nodes represent locations where there are structural changes instead. For example, a node may represent the location where the number of lanes reduces from four to three or increases from three to four. Links or arcs joining two nodes correspond to segments of freeways and arterials connecting to two intersections or interchanges. In most cases, links are bi-directional.

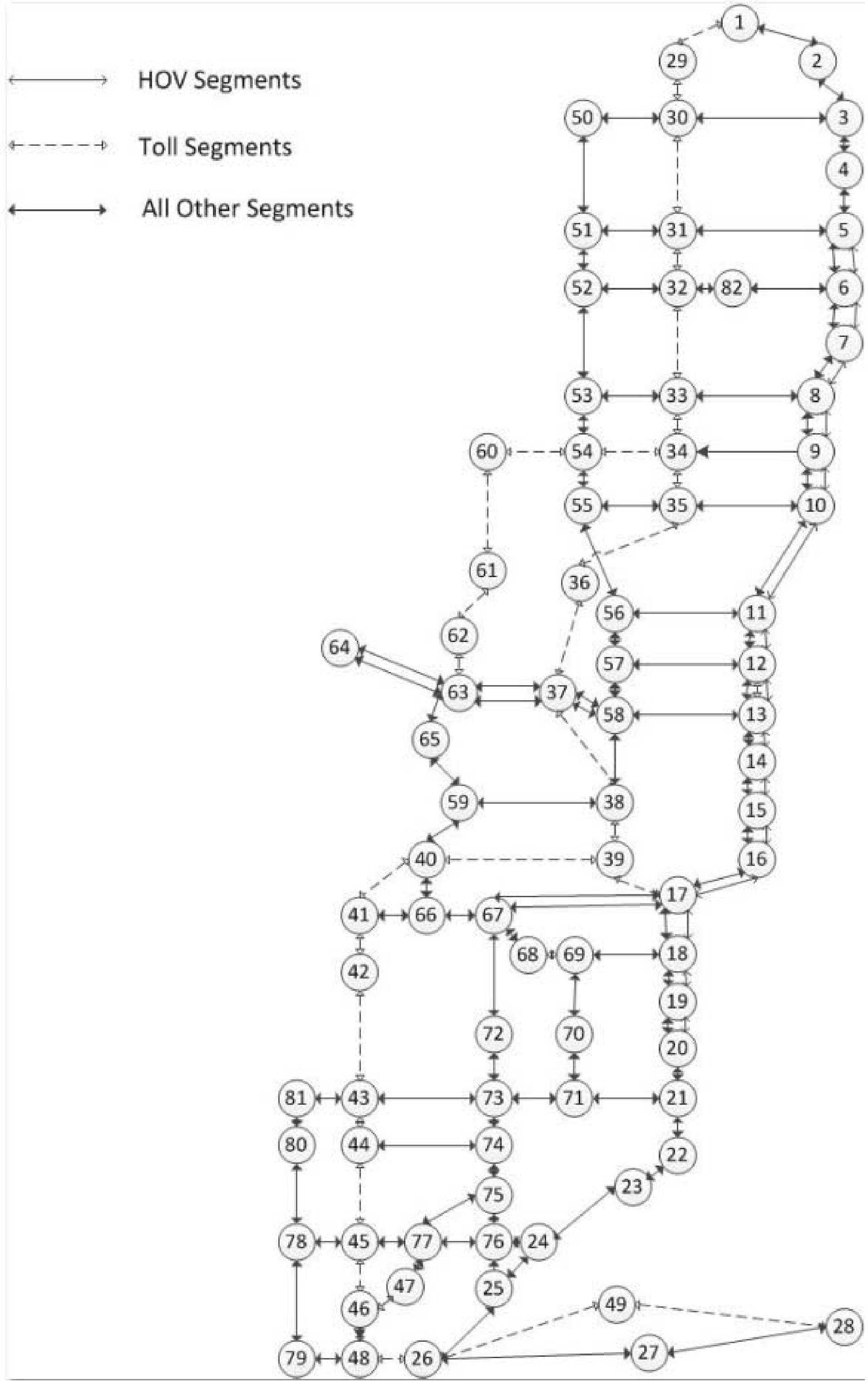


FIGURE 6.2 Network of Links and Nodes for South Florida

6.1.1 Estimating Travel Demands

Because demand data are not readily available, the first step for our case studies is to estimate travel demands between pairs of nodes shown in FIGURE 6.2. We assume that motorists use the network in FIGURE 6.2 to commute between home and work during peak travel period if such a trip is between 20 and 70 miles. Motorists use local streets for commuting trips shorter than 20 miles. Trips longer than 70 miles are less common and considered negligible. One method for estimating demands is to solve an O-D estimation problem similar to the one in Shen and Wynter (2012) using link flows and parameters from FSUTMS. However, demands estimated with such an approach did not lead to significant travel time improvements during our preliminary investigation. Instead, we generate our own travel demands.

Our set of demands includes 1013 O-D pairs and consists of 148,817 SOVs and 27,850 HOVs per hours during peak periods. TABLE 6.2 lists the demands (in vehicles per hour) that originates from nodes 1 to 5. Demands originating from other nodes are too numerous to list in this report. In TABLE 6.2, the demand to travel from node 4 to node 34 (or for O-D pair (4,34)) is on average 419.4 vehicles per hour during a peak travel period.

TABLE 6.2 Demand (in Vehicles per Hour) Originating from Nodes 1 to 5

(O, D)	SOV	HOV	(O,D)	SOV	HOV
(1,12)	36.3	6.5	**(4,22)**	27.6	5.2
(1,15)	42.2	7.7	**(4,34)**	419.4	74
(1,17)	41.7	7.8	**(4,37)**	32.9	5.9
(1,36)	28.4	5.1	**(4,38)**	39.4	7.2
(1,53)	35.3	6.2	**(4,58)**	29.3	5.3
(1,55)	28.3	5	**(4,59)**	32.2	6
(1,56)	32.9	5.9	**(4,62)**	29.4	5.4
(1,62)	36.9	6.7	**(4,63)**	35.8	6.5
(2,14)	27.3	5	**(4,64)**	25.9	4.7
(2,16)	32.5	6	**(4,65)**	41.3	7.5
(2,18)	27.8	5.3	**(4,71)**	30.8	5.9
(2,19)	31.8	6	**(5,15)**	412.6	75.1
(2,35)	27.2	4.8	**(5,22)**	35.1	6.7
(2,38)	33.4	6.2	**(5,23)**	25.3	4.8
(2,57)	26.3	4.7	**(5,29)**	404.3	71
(2,63)	39.5	7.2	**(5,42)**	33.8	6.4
(2,65)	33.1	6.1	**(5,47)**	39.1	7.5
(3,20)	40.5	7.7	**(5,56)**	402.7	71.7
(3,21)	41.7	7.9	**(5,59)**	41.5	7.7
(3,35)	387.9	68.6	**(5,62)**	421	76.4
(3,37)	31.1	5.6	**(5,65)**	27.2	5
(3,58)	39.6	7.2	**(5,67)**	38.4	7.2
(3,64)	40.1	7.3	**(5,68)**	37.9	7.1
(4,13)	33.2	6	**(5,71)**	27.9	5.3
(4,14)	40	7.3	**(5,74)**	35.3	6.8
(4,16)	25.7	4.7	**(5,75)**	39.1	7.5
(4,19)	28.6	5.4			

The user-equilibrium distribution associated with our demand data generates -21.90 units of equilibrium value[22] with average delays of 122.64 minutes (approximate 2 hours) and 75.38 minutes (approximately 1.25 hours) for SOVs and HOVs, respectively. Overall, the travel delay when averaged over both SOVs and HOVs is 118.59 minutes or 1.98 hours during a peak travel period. Although these delays seem excessive and, perhaps, unrealistic, we choose them to make the results in our case studies conspicuous.

[22] We refer to the objective value of the "diagonalized" problem in the Appendix as the "equilibrium value" associated with the user-equilibrium distribution.

6.2 Selection of Managed Arterial Lanes

This section describes a heuristic procedure called "steepest decrease" to add HOV lanes to arterials. (The procedure of adding and/or converting GP lanes to HOT lanes is similar. Our preliminary investigation using the above data indicates that the improvements associated with HOT implementations are less than those with HOV.)

In general, the SD procedure selects lanes on arterials for HOV implementation one at a time. Each time, the arterial that leads to the most decrease in the equilibrium value[23] is selected for HOV implementation. In our approach, we determine the equilibrium value associated with an HOV implementation on an arterial using the mathematical model and procedure described in the appendix. Strictly speaking, the procedure is heuristic because it is based an intuitive idea and does not necessarily yield an optimal solution. However, the managed lane selection problem as documented in the literature (see, e.g., Song et al., 2014) is difficult to solve optimally. Below, we first describe the SD procedure and subsequently illustrate it with an example using the network and data described in Section 6.1.

6.2.1 Steepest Decrease Procedure

The SD procedure requires as inputs a list of candidate arterials for HOV implementation. The basic idea is to consider a candidate arterial from the list one at a time and in an iterative fashion. During each iteration, we assume that we implement and remove from the candidate list all arterials chosen during the preceding iterations and consider individually the remaining candidate arterials still on the list one at a time. For each remaining candidate, we evaluate the impact of the HOV implementation using the procedure in the appendix. The one with the least (or the most decrease) equilibrium value is chosen for implementation and removed from the candidate prior to the next iteration. The process is repeated until the desired number of arterials has been selected. Below, we state the SD procedure formally assuming that there are Q candidate arterials for HOV implementation and k of these arterials are to be selected.

Steepest Decrease Procedure

Step 1: Put all Q arterials on a list called L and set $n = 0$.

Step 2: If $n = k$, then stop and the desired number of arterials have been chosen. Otherwise, go to Step 3.

Step 3: For each arterial on L, implement the HOV scheme and evaluate the impact using the procedure[24] in the appendix.

Step 4: Choose the arterial on L with the least equilibrium value for implementation and remove it from L. Set $n = n + 1$ (i.e., to indicate that we choose one additional arterial for an HOV implementation) and return to Step 2.

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[23] Other factors can be used instead of the equilibrium value. The underlying problem can be viewed as an optimization problem with two objectives, i.e., one is to minimize the average travel time of HOVs and the other is to minimize the same for SOVs. In the literature, a bi-objective optimization problem is difficult to solve and has multiple non-dominated solutions. Our steepest decrease procedure is a heuristic algorithm that relies on the equilibrium value as an estimate of the impact of a managed lane.

[24] It is also possible to FSUTMS instead of the procedure in the appendix.

6.2.2 Case Study

To illustrate the SD procedure, we assume that the set of candidate arterials consist of the following links: (23,24), (26,27) ,(38,58), (54,53), (57,56), (57,58), (66.41), (67,17), (69.18), (69.70), (80,81), (81.43). FIGURE 6.3 shows the locations of these links.) In our user-equilibrium distribution, the actual travel time on these links are at least twice as much as their free-flow travel times. As indicated earlier, the equilibrium value associated with the user-equilibrium distribution prior to any HOV implementation is -21.90.

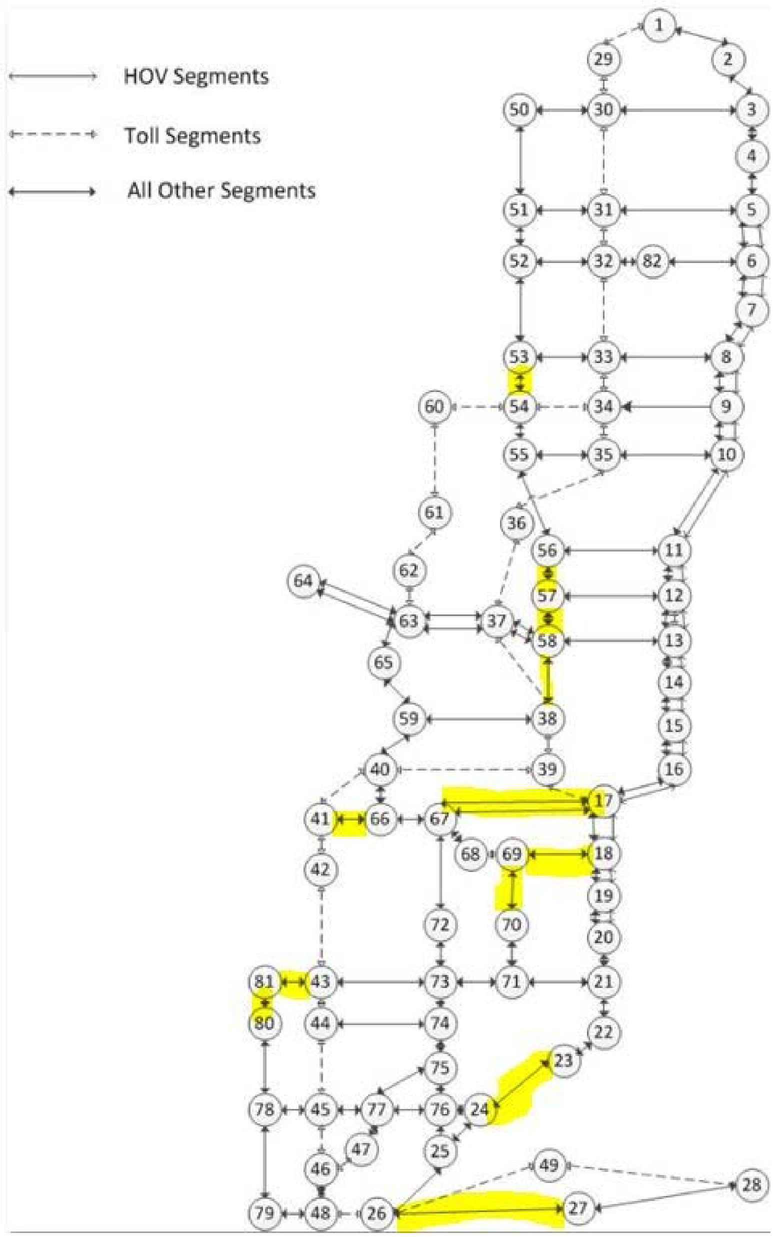

FIGURE 6.3 Locations of Candidates for HOV Implementations

For our experiment, if a candidate arterial has two lanes (in each direction), then our HOV implementation adds two HOV lanes to the arterial to generate more dramatic impacts. On the other hand, we only add one HOV lane to those candidate arterials with three or more GP lanes.

TABLE 6.3 displays the equilibrium values associated with each candidate arterial from four iterations of the SD procedure. During the first iteration, we implement the above HOV scheme on each candidate individually and the associated equilibrium values are listed in the column titled "Iteration 1." For example, when we implement the HOV scheme on link (23,24), the equilibrium value decreases from -21.90 to -21.9442. At the end of the first iteration, link (81,43) yields the most decrease in equilibrium value (-22.0912). Thus, we choose it for the HOV implementation. In Iteration 2, the procedure assumes that $(81{,}43)$ has new HOV lanes and seeks one additional arterial for HOV implementation. At the end of Iteration 2, link $(80{,}81)$ generates the smallest (or the most decrease) equilibrium value (-22.0915). Iterations 3 and 4 are similar. Observe that the equilibrium values for Iterations 2, 3 and 4 appear essentially the same because we round the value to four decimal places. When more decimal places are considered, these values are not the same. In any case, TABLE 6.3 indicates that implementing the HOV schemes on {(80, 81), (81, 43)} or {(80,81), (81,43), (67,17)} are sufficient because additional implementations would not yield significant decreases in equilibrium value.

TABLE 6.3 Equilibrium Values from SD Procedure

Candidate	Iteration 1	Iteration 2	Iteration 3	Iteration4
(23,24)	-21.9442	-22.0914	-22.0915	-22.0915
(26,27)	-21.9574	-22.0914	-22.0915	-22.0915
(38,58)	-22.0195	-22.0914	-22.0915	-22.0915
(54,53)	-22.0294	-22.0914	-22.0915	-22.0915
(57,56)	-22.0363	-22.0914	-22.0915	-22.0915
(57,58)	-22.0587	-22.0914	-22.0915	-22.0915
(66,41)	-22.0617	-22.0914	-22.0915	-22.0915
(67,17)	-22.0704	-22.0915	-22.0915	n/a
(69,18)	-22.0739	-22.0915	-22.0915	-22.0915
(69,70)	-22.0796	-22.0915	-22.0915	-22.0915
(80,81)	-22.0818	-22.0915	n/a	n/a
(81,43)	-22.0912	n/a	n/a	n/a
minimum	**-22.0912**	**-22.0915**	**-22.0915**	**-22.0915**

TABLE 6.4 to TABLE **6.6** display travel delays from the SD procedure for HOVs and SOVs, individually and averaged together. Except SOV travel delay in Iteration 4, all average delays appear to decrease or remain the same after each iteration of the SD procedure. In TABLE 6.4, the HOV travel delays decreases from 78.35 minutes (see Section 6.1.1) to 62.68 minutes or approximately 14%.

TABLE 6.4 Travel Delays for HOVs from SD Procedure

Candidate	Iteration 1	Iteration 2	Iteration 3	Iteration 4
(23,24)	73.2556	62.6804	62.6753	62.6751
(26,27)	72.4139	62.6778	62.6752	62.6751
(38,58)	67.6531	62.6774	62.6751	62.6751
(54,53)	66.9065	62.6767	62.6751	62.6751
(57,56)	66.4796	62.6765	62.6751	62.6751
(57,58)	64.7589	62.6761	62.6751	62.6751
(66,41)	64.4433	62.6756	62.6751	62.6751
(67,17)	64.0165	62.6755	62.6751	
(69,18)	63.6913	62.6754	62.6751	62.6751
(69,70)	63.3466	62.6754	62.6751	62.6751
(80,81)	63.2767	62.6753		
(81,43)	62.6844			
minimum	**62.6844**	**62.6753**	**62.6751**	**62.6751**

TABLE 6.5 Travel Delays for SOVs from SD Procedure

Candidate	Iteration 1	Iteration 2	Iteration 3	Iteration 4
(23,24)	122.1337	119.6834	119.6835	119.6835
(26,27)	121.9451	119.6836	119.6835	119.6835
(38,58)	120.7975	119.6837	119.6835	119.6835
(54,53)	120.6302	119.6837	119.6835	119.6835
(57,56)	120.5195	119.6836	119.6834	119.6835
(57,58)	120.1100	119.6836	119.6835	119.6835
(66,41)	120.0874	119.6835	119.6835	119.6835
(67,17)	119.9184	119.6835	119.6835	
(69,18)	119.9063	119.6835	119.6835	119.6835
(69,70)	119.7918	119.6835	119.6835	119.6835
(80,81)	119.7776	119.6835		
(81,43)	119.6842			
minimum	**119.6842**	**119.6834**	**119.6834**	**119.6835**

TABLE 6.6 Average Travel Delays for HOVs and SOVs from SD Procedure

Candidate	Iteration 1	Iteration 2	Iteration 3	Iteration 4
(23,24)	117.9531	114.8151	114.8148	114.8147
(26,27)	117.7094	114.8151	114.8148	114.8147
(38,58)	116.2560	114.8152	114.8147	114.8147
(54,53)	116.0393	114.8151	114.8147	114.8147
(57,56)	115.9020	114.8150	114.8147	114.8147
(57,58)	115.3816	114.8150	114.8147	114.8147
(66,41)	115.3338	114.8148	114.8147	114.8147
(67,17)	115.1436	114.8148	114.8147	
(69,18)	115.1045	114.8148	114.8147	114.8147
(69,70)	114.9708	114.8148	114.8147	114.8147
(80,81)	114.9518	114.8148		
(81,43)	114.8162			
minimum	**114.8162**	**114.8148**	**114.8147**	**114.8147**

6.3 Evaluation of Deployment Plans

In this section, we assume that a set of arterials have been selected for managed lane implementations, i.e., there is a plan for deploying managed lanes on arterials. The goal of this section is to describe a procedure that examines alternatives to this plan for possible improvements. If none exists or provides an improvement that is insignificant when considered in light of, e.g., political, equity, environmental and other issues, then the set of selected arterials is considered "optimal." Because it is beyond the scope of this projectto consider political or other previously mentioned issues, this section uses equilibrium values (mentioned in Section 6.1) as a measure of improvement.

Below, we describe a procedure called "pairwise interchange" to search for an alternative set of arterials with a better equilibrium value. As the name implies, the procedure tries to find a better alternative by interchanging or replacing a selected arterial with an alternative. (Note that this interchange involves a pair of arterials consisting of a selected arterial and an alternative.) If the interchange leads to an improvement, then the interchange becomes permanent. The process continues until no significant improvement is possible. As before, we illustrate the procedure using the network and data described in Section 6.1.

6.3.1 Pairwise Interchange Procedure

The PI procedure assumes that there exists a set of arterials selected for managed lane implementation. As done in Section 6.2, this section assumes that the implementation involves adding HOV lanes. The procedure is essentially the same when applied to HOT or a combination of HOV and HOT implementations. The procedure examines the improvement in equilibrium value gained from replacing a selected arterial with an alternative in a manner that ensures all possibilities are examined. To state the procedure formally, let S and A denote respectively the set of selected and alternative arterials, respectively. The latter can consist of, e.g., managed lane projects from MPO's long-range MTP or TIP.

Pairwise Interchange Procedure

Step 1: Evaluate the impact of adding HOV lanes to arterials in S using the procedure in the appendix. Set β equal to the associated equilibrium value.

Step 2: For each arterial in S (denoted as i) and each one in A (denoted as j)[25], evaluate the impact on the equilibrium value (using the procedure in the appendix) when we add HOV lanes to j instead of i.

Step 3: Let pair $(\hat{\imath}, \hat{\jmath})$ yields the least equilibrium value and ηdenote this value. If ηrepresents a significant improvement to β, then stop and the arterials in S is optimal. Otherwise, remove arterial $\hat{\imath}$ from S and add it to A and, similarly, remove $\hat{\jmath}$ from A and add it to S. Return to Step 2.

6.3.2 Case Study

To illustrate the PI procedure, we assume that S (the set of selected arterials) and A (the set of alternatives) are defined as follows:

$$S = \{(58, 57), (66, 41), (81, 43)\}$$

$$A = \{(26, 27), (38, 58), (54, 53), (67, 17), (69, 18), (80, 81)\}$$

Below, we evaluate whether S is the best set of arterials to implement using the PI procedure to explore whether there is a better alternative.

TABLE 6.7 displays the details concerning each iteration of the PI procedure. Note that members of S are used to label the rows and those in A label the columns. The improvements due to the pairwise interchange of elements of the above S and A are displayed under "Iteration 1" heading. Note that replacing $(66{,}41)$ with $(58{,}53)$ yields the largest improvement in equilibrium value. After the interchange, S and A become $S = \{(58, 57), (58, 38), (81, 43)\}$ and $A = \{(26, 27), (54, 53), (66{,}41), (67, 17), (69, 18), (80, 81)\}$. At which point, the second iteration of the procedure begins. At the end of this iteration, we replace $(81{,}43)$ with $(54{,}53)$. Similarly, we replace $(54{,}53)$ with $(26{,}27)$ at the end of the third iteration. Finally, Iteration 4 proves that no pairwise interchange leads to any improvement and the procedure terminates. The final set of selected arterials for HOV implementation consists of $\{(26{,}27), (58{,}38), (58{,}57)\}$. Finally, TABLE 6.8 displays how travel delays and equilibrium values as the PI procedure progresses. While the improvements for SOV delays and equilibrium values from the first to third iterations seem small, the decrease in HOV travel delays (7.7%) is significant.

25 Mathematically, we consider every possible pair (i, j) where $i \in S$ and $j \in A$.

TABLE 6.7 Iterations from PI Procedure

Iteration 1

	(26,27)	(54,53)	(58,38)	(67,17)	(69,18)	(80,81)
(58,57)	0	0	0.0482	0.0027	0	0
(66,41)	0.008	0.0097	0.0683	0.0132	0.0069	0
(81,43)	0.0032	0.0036	0.0615	0.006	0	0

Iteration 2

	(26,27)	(54,53)	(66,41)	(67,17)	(69,18)	(80,81)
(58,38)	0	0	0	0	0	0
(58,57)	0	0	0	0	0	0
(81,43)	0.0004	0.0065	0	0.004	0.0031	0

Iteration 3

	(26,27)	(66,41)	(67,17)	(69,18)	(80,81)	(81,43)
(54,53)	0.0073	0	0.0035	0.0021	0	0
(58,38)	0	0	0	0	0	0
(58,57)	0	0	0	0	0	0

Iteration 4

	(54,53)	(66,41)	(67,17)	(69,18)	(80,81)	(81,43)
(26,27)	0	0	0	0	0	0
(58,38)	0	0	0	0	0	0
(58,57)	0	0	0	0	0	0

TABLE 6.8 Travel Delays (in minutes) and Equilibrium Value for PI Procedure

Iteration	SOV Ave	HOV Ave	All Ave	Equil. Value
1	122.23	72.96	118.02	-21.93
2	121.00	67.85	116.45	-22.00
3	120.82	67.31	116.24	-22.01

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APPENDIX A: USER-EQUILIBRIUM MODEL FOR COMBINED ROUTE AND MODE CHOICE

In this section, we describe a model for finding a user-equilibrium flow distribution in a network of nodes and links. The latter may be parallel to represent individual lanes of different types on the same road segment.

Let $G(\mathcal{N},\mathcal{A})$ denote the network of freeways and arterials where $\mathcal{N}$ and $\mathcal{A}$ represent the set of nodes and arcs. Moreover, $\mathcal{A} = \mathcal{A}_f \cup \mathcal{A}_a \cup \mathcal{A}_h \cup \mathcal{A}_t$ where $\mathcal{A}_f, \mathcal{A}_a, \mathcal{A}_h$ and $\mathcal{A}_t$ consist of links corresponding to freeways, arterials, HOV lanes, and tolled freeways and arterials, respectively. For simplicity, we assume that there are two types of vehicles, SOVs and HOVs, and their flows on link (i,j) for OD pair $w \in \mathcal{W}$ (where $\mathcal{W}$ is the set of all OD pairs) are denoted as x_{ij}^w and y_{ij}^w, respectively. The travel demands for SOVs and HOVs are denoted as d_x^w and d_y^w, respectively. We also let x and y represent the vectors of individual x_{ij}^w and y_{ij}^w, respectively. Then, a pair of vectors (x, y, d_x, d_y) is feasible if they belong to the following set:

$$\mathcal{F} = \left\{(x, y, d_x, d_y) \middle| A_x x^w = d_x^w E^w, A_y y^w = d_y^w E^w, x^w, y^w \geq 0, \forall w \in \mathcal{W}\right\}$$

In the above, A_x is the node-arc incidence matrix for the subnetwork $G(\mathcal{N},\mathcal{A}_x)$, where $\mathcal{A}_x = \mathcal{A}_f \cup \mathcal{A}_a \cup \mathcal{A}_t$, i.e., $\mathcal{A}_x$ consists of links traversable by SOVs. Similarly, A_y is the node-arc incidence matrix of $G(\mathcal{N},\mathcal{A})$ because HOVs can travel on every link. In addition, E^w is a vector with 1 in the component corresponding to the origin node of OD pair w and with -1 in the component corresponding to the destination. The remaining components of E^w are zero.

Then, $(\hat{x}, \hat{y}, \hat{d}_x, \hat{d}_y)$ is a user-equilibrium flow distribution if it satisfies the following variational inequality, i.e., for all $(x, y, d_x, d_y) \in \mathcal{F}$, the following holds:

$$(t(\hat{z}) + \tau)^T (x - \hat{x}) + t(\hat{z})^T (y - \hat{y}) - \frac{1}{\theta} \sum_{w \in \mathcal{W}} \ln(\hat{d}_x^w + \beta_x)(d_x^w - \hat{d}_x^w) + \ln(\hat{d}_y^w + \beta_y)(d_y^w - \hat{d}_y^w) \geq 0$$

where $\hat{z} = \hat{x} + \hat{y}$, τ is a toll vector, and the remaining (i.e., θ, β_x and β_y) are logit parameters.

For the results in Sections 6.1, 6.2.2 and 6.3.2, we find an approximate solution to the above variational inequality using the diagonalization algorithm implemented in GAMS (www.gams.com), a software for algebraic modeling. The diagonalization algorithm finds an approximate solution to the above by solving a sequence of related optimization problems. We refer to the optimal objective value to the final optimization problem as the "equilibrium value" the variational inequality.

APPENDIX B. PRESENTATION MATERIALS

Below are the presentations used for the progress report meetings during the project.

Kick-Off Meeting for BDV32 TWO 977-01, 3/8/2013

Deployment Strategies of Managed Lanes on Arterials

1

Managed Lanes

- Highway facilities or a set of lanes where operational strategies are proactively implemented and managed. The principal management strategies can be categorized into three groups: vehicle eligibility, pricing, and access control.
  - High-occupancy vehicle (HOV) lanes
  - Bus- or truck-only lanes
  - High-occupancy/toll (HOT) lanes
  - Express toll lanes
  - Reversible lanes
  - Contra-flow lanes

2

Objective

- Examine managed-lane deployment strategies on arterials
- Identify tools to evaluate their performances
- Investigate ways to coordinate the deployment and operations of managed lanes on both limited-access facilities and arterials

3

Basic Information

- Project Period
  - 02/11/2013 thru 11/30/2014
- Project Manager
  - Holly Walker
- Principle Investigators
  - Yafeng Yin
  - Toi Lawphongpanich

4

Supporting Tasks

- Task 1: *Review of State and National Practices of Managed Lanes on Arterials*
  - Lead: Toi Lawphongpanich
  - Assistant: Ximing Wang
  - Purpose: conduct a literature review of existing managed lane deployments on arterials in Florida and around the country

5

Supporting Tasks (Cont'd)

- Task 2: *Identification and Selection of Managed Lane Strategies*
  - Lead: Yafeng Yin
  - Assistant: Mahmood Zangui
  - Purpose: identify the types of managed lanes and their variants with potentials for managing traffic along arterials in Florida

6

Supporting Tasks (Cont'd)

- Task 3: *Implementation and Monitoring Program*
  - Lead: Toi Lawphongpanich
  - Assistant: Ximing Wang
  - Purpose: identify potential revenue sources and develop phased implementation schedules and monitoring schedules, including agency responsibilities

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Supporting Tasks (Cont'd)

- Task 4: *Identification of Evaluation Tools*
  - Lead: Yafeng Yin
  - Assistant: Mahmood Zangui
  - Purpose: identify quantitative tools for evaluating the performances of various deployments of managed lanes. The task will examine the suitability of various tools to evaluate a certain type of managed lanes, and identify the needs of further enhancements, if necessary

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Supporting Tasks (Cont'd)

- Task 5: *Managed Lanes on Limited Access Facilities and Arterials*
  - Lead: Yafeng Yin and Toi Lawphongpanich
  - Assistant: To be determined
  - Purpose: explore the impacts that managed lanes on limited access facilities have on the surrounding arterial network and the possibility for coordinated deployment and operations of managed lanes on arterials

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Supporting Tasks (Cont'd)

- Task 6: Meetings
  - Lead: Yafeng Yin
- Task 7: Draft and Final Report
  - Lead: Yafeng Yin

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Deliverables

Report #	Report Due Date
Task 1	June 30, 2013
Task 2	February 28, 2014
Task 3	December 31, 2013
Task 4	July 31, 2014
Task 5	July 31, 2014
Task 6	July 31, 2014
Draft Final	August 30, 2014
Final	November 30, 2014

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Deployment Strategies on Managed Lanes on Arterials (Contract BDV32 977-01)

Task 1: Review of Practices of Managed Lanes on Arterials

PI: Yafeng Yin
Co-PI: Siriphong (Toi) Lawphongpanich
12-Jul-2013

Outline

- Operating Environment on Arterials
- Flow Management Approaches
- Types of Managed Facilities
- Designs and Implementation
- Objectives
- Strategies
- Planning
- Performance
- Public Attitude

Operating Environment on Arterials

- Arterials provide access to local streets and business.
- Speed limits on arterials are between 35 and 50 mph.
- There are intersections (signalized or otherwise) on arterials.
- Buses, cars, and commercial vehicles stop along arterials to load/unload passengers, access local business, and make deliveries, respectively.
- Vehicles on arterials often travel at different speeds.

Flow Management Approaches

- Three approaches for managing travel demand.
  - Restricting vehicle eligibility
  - Imposing usage fees.
  - Limiting vehicle access
    - It is not clear that limiting vehicle access (e.g., via ramp metering or dedicated access ramps) are possible or practical on arterials.

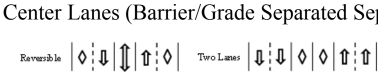
Types of Managed Facilities on Arterials

- Managed facilities with restricted eligibilities
  - HOV Lanes
  - Bus-only Lanes
- Price-managed facilities
  - HOT Lanes
  - Bus-Toll Lanes
  - Truck-only Toll Lanes
  - Express Toll Lanes

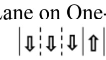
Designs and Implementation

- Concurrent Flow Lanes
  - Curbside, Second, and Left-side Lane

- Center Lanes (Barrier/Grade Separated Separated)



- Contraflow Lane on One-Way Street



Designs and Implementation (Cont.)

- Priority Treatments at Intersections

Implementation Objectives

- Maintain and/or enhance mobility
- Improve roadway operation efficiency, safety and reliability.
- Improve air quality
- Promote transit and ridesharing
- Provide faster and/or more reliable travel option
- Generate revenue

Strategies

- Arterials with HOV lanes should have minimal turning movements, signalized intersections and access to abutting properties.
- Queue jumps play an important role particularly at recurrent bottlenecks, overloaded intersections and system constrictors such as tunnels and bridges.
- Minimum Traffic volumes
  - Bus-only Lane (50 – 80 vphpl)
  - Contraflow bus-lane on one-way street (50 – 80 vphpl)
  - Concurrent HOV Lane (200 – 400 vphpl)
  - Reversible Single Barrier separated HOV Lane in the center (80 – 160 vphpl)

Planning

- Involved agencies include
  - Local municipalities
  - Transit agency
  - State DOT
  - Local and state police
  - Rideshare agency (if exists)
  - MPO
  - Federal Agencies
  - Other groups
    - Local judicial system, EMS, fire department, tow truck operators, businesses, and neighborhood groups

Performance

- The performance of HOV facilities on arterials has been mixed.
  - Bus-only lanes in NYC
    - Saved up to 30 minutes in travel times
    - Increased bus ridership by 7%
    - Significantly improved performance of bus lines using bus-only lanes
  - Bus-only lanes in Chicago suspended following pedestrian deaths.
  - Curbside bus-only lanes increased travel times. (Crowel, 1978)
  - 16 at-grade queue jumps suspended because of delays caused by other traffics, high maintenance costs, etc.

Public Attitude

- 75% of survey respondents in Orange County (CA) expressed positive attitudes toward an HOV lane “test.”
- 90% of survey respondents in Seattle were either somewhat or strongly support the idea of bus and carpool lanes.
- 99% of people in Seattle were aware of HOV lanes and 80% did not think that they were unfair to non-users.

Next Tasks

- Task 2: Identification and Selection of Managed Lane Strategies (Due: 28-Feb-2014)
  - Identify types of managed lanes and their variants
  - Conditions for successful and effective application of each type.
- Task 3: Implementation and Monitoring Program (Due: 31-Dec-2013)
  - Identify potential revenue sources
  - Develop phased implementation and monitoring schedules, including agency responsibilities.

Project Meeting, 3/21/2014

Deployment Strategies of Managed Lanes on Arterials

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Today's Agenda

- **Task Overview: Chris Francis (5 min)**
- **Project Overview: Yafeng Yin (5 min)**
- **Task 1: Toi Lawphongpanich (15 min)**
- **Task 2: Yafeng Yin (20 min)**
- **Task 3: Siriphong Lawphongpanich (15 min)**

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Task Overview

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Basic Information

- **Project Period**
  - **02/11/2013 thru 11/30/2014**
- **Project Manager**
  - **Chris Francis**
- **Principle Investigators**
  - **Yafeng Yin**
  - **Toi Lawphongpanich**

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Tasks

- **Task 1:** ***Review of State and National Practices of Managed Lanes on Arterials***
- **Task 2:** ***Identification and Selection of Managed Lane Strategies***
- **Task 3:** ***Implementation and Monitoring Program***
- **Task 4:** ***Identification of Evaluation Tools***
- **Task 5:** ***Managed Lanes on Limited Access Facilities and Arterials***
- **Task 6:** ***Meetings***
- **Task 7:** ***Draft and Final Report***

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Work Plan

Report #	Report Due Date	Progress Meeting	Presentation
Task 1	June 30, 2013		
Task 2	February 28, 2014	March 7, 2014	March 21, 2014
Task 3	December 31, 2013	February 7, 2014	March 21, 2014
Task 4	July 31, 2014	April 11, May 9 and June 13, August 15, 2014	July 25, 2014
Task 5	July 31, 2014		
Task 6	July 31, 2014		
Draft Final	August 30, 2014		September 19
Final	November 30, 2014		

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Project Overview

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Research Objective

- Examine managed-lane deployment strategies on arterials
- Identify tools to evaluate their performances
- Investigate ways to coordinate the deployment and operations of managed lanes on both limited-access facilities and arterials

8

Managed-Lane Strategies

- A managed-lane strategy is defined as a combination of three aspects, including the type of the managed lane, its design and implementation, and associated traffic management schemes.
  - For example, a busy-only lane can be placed on the median of a two-way arterial or is a contraflow lane at a one-way arterial. Further, various traffic management schemes, such as transit signal priority and queue jumps, may be provided to enhance its performance.

9

Types of Managed Lanes

- We classify managed lanes into a few major types based on their management or control approaches, i.e., vehicle eligibility, access control or pricing
  - High-occupancy-vehicle (HOV) lanes
  - High-occupancy-toll (HOT) lanes
  - Bus-only lanes
  - Truck-only lanes
  - Express-toll (ET) lanes
  - Bus-toll lanes
  - Truck-toll lanes

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Arterial

- An arterial is a high-capacity urban road whose primary function is to deliver traffic from collector roads to freeways, and between urban centers at the highest level of service possible. As such, many arteries are limited-access roads, or feature restrictions on private access.

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Task 1: Review of State and National Practices of Managed Lanes on Arterials

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Definitions

- **HOV Lanes:** Allow access to high-occupancy vehicles and, perhaps, motorcycles, electric and hybrid vehicles.
- **HOT Lanes:** Allow access to non-HOV for a fee

HOV Lane in Santa Clara County, CA

Definitions (cont.)

- **Bus-Only Lanes:** Allow access only to buses
- **Bus-Toll Lanes:** Allow access to other types of vehicles of a fee

Bus-Only Lane in Roosevelt Road, Taipei, Taiwan

Contra-flow Bus-Only Lane, Spring Street, Los Angles, CA

Definitions (cont.)

- **Express-Toll (ET) Lane:** Every vehicle must pay tolls to access.
- **Truck-Only Lane**
- **Truck-Only Toll (TOT) Lane**

Key Findings: Current Practice

- **There are many managed freeway lanes in the U.S. (FHWA, Office of Operations)**
  - **345 HOV facilities**
    - **307 operational, 10 being planned, 15 under environmental review, 14 under construction**
    - **Purely 2+: 185 (54%), Purely 3+: 14 (4%)**
      - **Some operates like HOT lanes.**
    - **California: 88, Minnesota: 83, Washington State:41**
    - **I-395 HOV lanes in Virginia opened in 1969**
    - **Majority opened after 1980**
  - **13 HOT facilities (200 miles)**
    - **SR 91 in Orange County, CA opened in Jan. 2003**

Key Findings: Current Practice (cont.)

- **The number of managed arterial lanes in the U.S. is relatively small.**
  - **Nine HOV facilities on arterials (from our review)**
    - **South Dixie Highway (Miami, FL):**
      - **Opened 1974, 5.5 miles, Occupancy Req.: 3+**
  - **41 Bus facilities (Bus Streets/Malls, Bus lanes) in 17 cites**
    - **Spring Street bus-only lane (Los Angeles, CA)**
      - **Opened 1974, 1.5 miles, contraflow**
  - **In 1986, Batz reviewed 95 bus/HOV lanes.**
    - **33 successful**
    - **22 suspended, 11 under suspension consideration**
    - **9 out of 16 signal treatments suspended: delays imposed on other traffic, costs, and other reasons**

Examples of HOV Lanes on Arterials

Selected Implementations of Arterial HOV Lanes

Location	Year opened	Length (mile)	Travel Time Saving (min)	Occupancy Requirement
Airport Rd, Seattle, WA	1993	3.4	1	2+
Capitol Expy., Santa Clara, CA	1997	3.8	1.1 AM Peak 0.4 PM Peak	2+
Montague Expy., Santa Clara, CA	1983	5.4	3.8 AM Peak 0.0 PM Peak	2+
San Tomas Expy., Santa Clara, CA	1982	7.2	3.1 AM Peak 2.9 PM Peak	2+

Examples of Bus-Only Lane on Arterials

Selected Implementations of Arterial Bus-Only Lanes

Location	Route	Length (mile)	Average Operational Speed (MPH)	Average Weekday Ridership
Everett, WA	Swift BRT-SR 99	16.7	24	4,300
Eugene, OR	Franklin EmX	4	17	6,000
Los Angeles, CA	705 La Cienega-Vernon Rapid	14.1	12.5	7,994
New York, NY	M15	8.5	10	57,000
Nashville, TN	Route 56 BRT Gallatin Road	12	14	1,800
Washoe County, NV	RTC RAPID	4.2	11.3	3,000

Key Findings: Current Practice (cont.)

- There is no true express-toll lane in the U.S.
  - Maryland will open its I-95 ET lane later this year.
- There are very few truck-only facilities in the U.S.
  - There is no TOT lanes.
    - Studies and plans for TOT lanes in Los Angeles, Atlanta, and Virginia did not move forward into construction.

Key Findings: Objectives

- Objectives when managed by eligibility
  - Increase people-moving capacity
  - Reduce congestion
  - Provide travel time and cost savings
  - Increase system efficiency
  - Improve air quality
  - Enhance bus transit operations
  - Provide predictable travel times

Key findings: Objectives (cont.)

- Objectives when managed by price
  - Traffic Management: Optimal use of freeway capacity, reduce congestion, and a better management of traffic volume and condition.
  - Revenue Generation: Generate revenue to pay for the cost of implementing and operating the lanes and to support other transportation needs.
  - New Travel Options: Provide new options to motorists (particularly solo drivers) in congested freeways.
  - Enhance Transit Service: Provide faster transit service and improve travel-time reliability.

Public Acceptance

- Issues
  - Project Benefits and Goals
  - Travel Impacts
  - Project Cost and Use of Funds
  - Equity and Fairness
  - Technology Concerns
  - Enforcement
  - Environmental Impacts

Task 2: Identification and Selection of Managed Lane Strategies

Identification

- Identify managed lane strategies that have potentials for managing traffic along arterials in Florida
  - Types of Arterial Managed Lanes
  - Design and Implementation of Managed Lanes
  - Traffic Management Schemes

Types of Managed Lanes

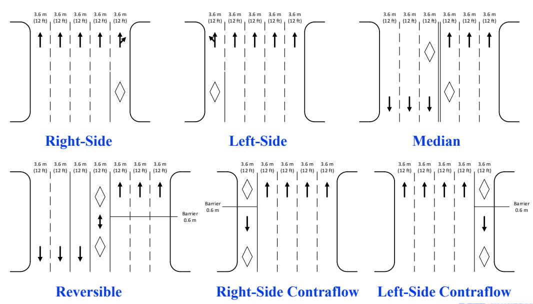
- Types to consider
  - High-occupancy-vehicle (HOV) lanes
  - Bus-only lanes
  - ~~Truck-only lanes~~
  - High-occupancy-toll (HOT) lanes
  - Express-toll (ET) lanes
  - Bus-toll lanes
  - ~~Truck-toll lanes~~

Toll Lanes

Design and Implementation

- The design and implementation of a managed lane involves six aspects:
  - Layout and placement
  - Lane length and width
  - Lane separations
  - Signs and markings
  - Access points
  - Pedestrian and bicycle conflicts

Layout and Placement



Layout and Placement (Cont'd)

Right-Side Managed Lane in Santa Clara County, CA

Layout and Placement (Cont'd)

Reversible Managed Lane on Lions Gate Bridge, Stanley Park, Vancouver

Layout and Placement (Cont'd)

Right-Side Contraflow Bus-Only Lane in San Juan, Puerto Rico

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Layout and Placement (Cont'd)

Layout	Pros	Cons
Right-side	Easy to implement	Parking and deliveries need to be addressed
Left-side	Offer higher speed and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Median	Offer higher speed and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Reversible	Make use of capacity in the non-peak direction and do not affect curb activities	Inconvenient for local transit and left-turn vehicles at GP lanes
Right-side contraflow	Make use of capacity in the non-peak direction	Usually limited to bus-only lanes
Left-side contraflow	Make use of capacity in the non-peak direction	Usually limited to bus-only lanes and need to address the bus stop issue

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Lane Length and Width

- The length of a managed lane may vary from one to several blocks, depending on its purpose
- All lanes are typically 3.6 m wide, not less than 3.3 m, except that:
  - If there are active pedestrian movements, it should be 4.0 to 4.3 m
  - If there are barrier separations, it should be 0.6 to 1.2 m wider

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Lane Separations

- There are three primary types of separation, including striping, buffer separation using plastic tubes, and concrete barriers

Buffer-Separation in 95 Express, Florida

Concrete Barriers in I-15 Express, San Diego

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Lane Separations (Cont'd)

Separation Types	Advantages	Disadvantages
Striping	Cheapest to implement; very low maintenance cost; unconstrained access of emergency and police vehicles	Higher number of violations; safety and operational concerns
Plastic Tubes	Require less right-of-way; less installation cost than concrete barriers; easier enforcement than striping; easy access for emergency vehicles	More expensive than striping; higher maintenance cost
Concrete Barriers	Eliminate unlawful weaving; improve safety; reduce mental stress of drivers	Very high construction cost; limit the access of emergency and police vehicles; wider buffer area

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Signs and Markings

- Signs and markings need to be provided to highlight the operations of managed lanes. All of them need to be remarkable and easy to understand
- Their design and implementation should follow the Manual of Urban Traffic Control Devices (MUTCD)

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Signs and Markings (Cont'd)

Examples of Signs of Managed Lanes

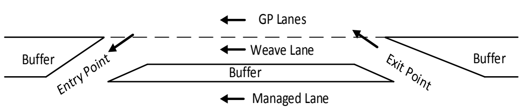
Example of Markings of Managed Lanes

Access Points

- The design of access points will largely depend on the type, layout and placement of a managed lane and the means of separation
  - For contraflow managed lanes, access points will usually be at intersection
  - For concurrent managed lanes, access points may be continuous
- Frequent access points provide convenience to drivers but may cause safety issues and interrupt traffic flow

Access Points (Cont'd)

- A weave lane can sometimes added to better maintain speed and throughput in the managed lane



Example of Weave Lane used for Access Points Design

Pedestrian and Bicycle Conflicts

- If managed lanes are newly added, pedestrian conflicts need to be considered carefully
  - Mid-street refuge islands can be provided as well as pedestrian skywalks or tunnels
  - The walking phase of signal control can be made longer and the vehicle speed limit set to be lower
- For curb-side concurrent managed lanes, one bicycle lane can be added next to the managed lane or the lane can be widened to accommodate bicycles

Pedestrian and Bicycle Conflicts (Cont'd)

Examples of Managed Lanes Accommodating Bicycles

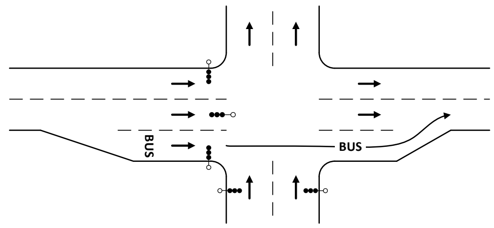
Traffic Management Schemes

- Various traffic management schemes can be used to enhance the performance of arterial manage lanes. They fall into one of the following three categories:
  - Intersection treatment
  - Segment management
  - Enforcement

Intersection Treatments

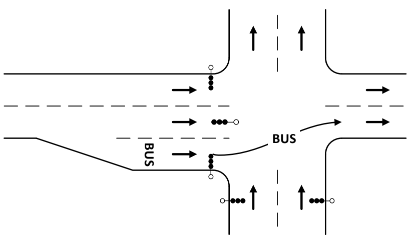
- Turning movement management
  - Prohibit or limit turning movements of GP vehicles that will interfere with the operations of managed lanes
- Queue jump
  - Provide the priority of passage to vehicles on managed lanes at intersections
- Signal control
  - Offer eligible vehicles additional preferential treatment

Queue Jump



Queue Jump Continued Lane

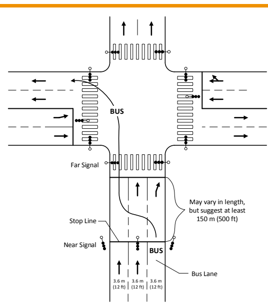
Queue Jump (Cont'd)



Queue Jump Lane with Designated Signal

Example

Queue Jump (Cont'd)



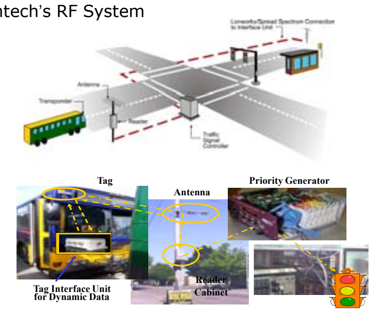
Queue Jump with Bus Advance Area

Signal Control

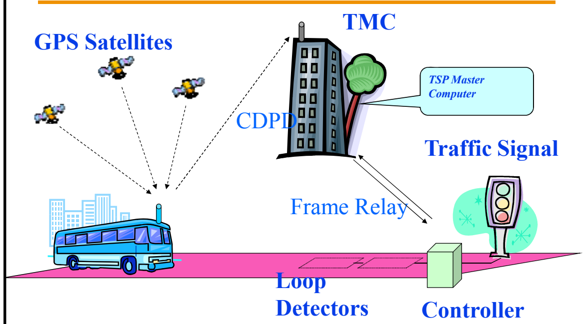
- Signal timing
  - Coordinate signals along the direction of managed lanes
  - Designate a phase to managed lanes at certain intersections
- Signal priority
  - Provide early green or green extension to accommodate the passing of an eligible vehicle at a signalized intersection

Example of Signal Priority

Amtech's RF System



Example of Signal Priority



Segment Management

- Pricing strategies
  - Set a right toll price for the successful operation of toll lanes
- Speed limits
  - Limit the difference of speed limits between managed and GP lanes
  - Variable speed limits should not be deployed for the purpose of preventing traffic flow breakdown or eliminating shockwaves, as they are expected to achieve at freeways

Pricing Strategies

- Zone-based toll structure
  - A motorist pays a toll when entering a new zone
- Origin-specific toll structure
  - Depend on where the motorist enters the facility
- OD-based toll structure
  - Depend on the origin and destination of the motorist
- Distance-based toll structure
  - Depend on the distance that the motorist travels on the facility

Pricing Strategies (Cont'd)

Toll structure	Pros	Cons
Zone-based	Easy to implement, particularly when expanded from a single-segment HOT facility	Additional lane changes at the beginning of each zone may cause disruptions; difficulty of balancing utilization of capacity and the disruptions caused by lane changes
Origin-specific	Easy to implement and convenient for users	Inefficient utilization of capacity possible inequality concerns
OD-based	Effectively manage demand and utilize capacity	More costly to implement
Distance-based	No equity concern	More costly to implement inefficient utilization of capacity

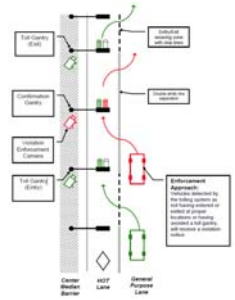
Automatic Enforcement

- Violation types
  - Vehicle eligibility violations
  - Unauthorized entries/exits
- Key technologies
  - Near-infrared camera
  - Electronic barrier system

Automatic Enforcement (Cont'd)

Near-Infrared Cameras

Automatic Enforcement (Cont'd)

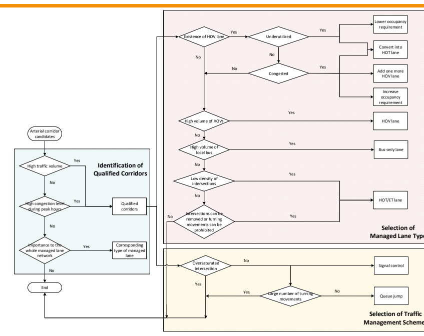


Electronic Barrier System

Selection and Screening Process

- Managed lane selection and screening process
  - Identification of qualified corridors
  - Selection of managed lane type
  - Selection of traffic management schemes
- Criteria for qualified corridors
  - High traffic volume
  - High level of congestion during peak hour
  - Importance to a managed lane network

Selection and Screening Process



Task 3: Implementation and Monitoring Program

Overview

- Selection and Screening Process: Part of Congestion Management Process or CMP?
  - A federal requirement for Transportation Management Areas (TMAs)
    - MPO with population exceeding 200,000
- Eight CMP actions
  - Develop Regional Objectives for Congestion Management
  - Define CMP Network (geographical scopes & system elements.)
  - Develop Multimodal Performance Measures
  - Collect Data/Monitoring System Performance
  - Analyze Congestion Problem and Needs
  - Identify and Access Strategies
  - Program and Implement Strategies
  - Evaluate Strategy Effectiveness

Overview (cont.)

- Planning
  - The project should be included into MPO's long-rang Metropolitan Transportation Plan (MTP) and Transportation Improvement Program (TIP)
  - Complete National Environmental Protection Act (NEPA) environmental clearance documents.
  - Approval through a Categorical Exclusion, FONSI, or Record of Decision (ROD) upon a completion of EIS.

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Overview (cont.)

- Design and Procurement:
  - MPO and NEPA requirements and funding commitments have been completed and secured.
  - Design work completes
  - Project puts out for bids.
    - Design-Bid-Build (DBB)
    - Design-Build (DB)
    - Design-Build-Finance-Operate-Maintain (DBFOM)

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Overview (cont.)

- Construction
- Operation and Maintenance
  - With DBB or DB procurements, the project sponsor assumes responsibility for maintaining and operating the managed facility
  - For DBFOM, the private developer operates and maintains the facility for a designated concession period.
- Public Outreach
  - Occur nearly throughout the entire project

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Roles and Responsibility

- Agencies
  - State DOT or its district offices
  - Turnpike/Toll Authority
  - MPO and Other Local Agencies
  - Transit Agencies
  - Private Development Partners
  - Private Consultant Contractors
  - Law Enforcement Agency/Emergency Response

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Roles and Responsibilities (Cont.)

- Responsibilities
  - Project Development
    - Planning/Technical Studies
    - Education and Public Outreach
    - Federal Programs and Grant Applications
    - Environmental Review/Permitting
    - Project Finance
    - Contract Award and Administration
    - Design
    - Construction

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Roles and Responsibilities (Cont.)

- Operations
  - Toll Collection and Billing, if appropriate
  - Traffic Management Center
  - Traveler Information
  - Facility Operations
  - Performance Monitoring/Management
  - Maintenance Operations
  - Enforcement
  - Incident Management
  - Customer Service
  - Marketing
  - Transit Operations, if appropriate

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Project Sponsor

- Project Sponsor
  - Champion the project
  - Can be responsible for nearly all activities
    - Executes planning studies
    - Submits applications and environmental documentation
    - Oversees construction and possibly the operation of the facility
  - Must understand institutional relationships.
    - Address any pre-existing political and institutional issues.
  - Typical choices for a project sponsor include
    - State DOT or its district offices
    - Turnpike/Toll Authority
    - MPO and Other Local Agencies
    - Transit Agencies

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Federal Programs and Requirement

- Section 129 Tolling Program
  - Tolling eligibilities and agreement requirements
- Tolling Programs
  - Value Pricing Pilot Program
  - Express Lanes Demonstration Program
  - Interstate System Construction Toll Pilot Program
  - Interstate System Reconstruction and Rehabilitation Pilot Program
- Major Project Requirements
  - Title 23 defines Major Projects as highway improvement requiring federal assistance that are over $500 million in cost.
  - Processes and federal requirements are more complex

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State Processes and Requirements for Tolling

- Must comply with state and local laws on toll collection.
- Variable Pricing Authority
- Public-Private Partnership Authority

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Public Outreach

- Stakeholder Identification: local residence, neighborhood groups and associations, elected officials, neighboring counties, municipalities, or towns, etc.
- Sharing Information
- Citizens' Advisory Committee/Community Task Force
- Executive Advisory Committee
- Marketing and Refining the Concept.

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Financing

- Federal Demonstration Funds
- State Funds, e.g., State Infrastructure Bank (SIB)
- Bonding and Debt Instruments:
  - Grant Anticipation Revenue Vehicle (GARVEE) Bonds
  - Private Activity Bonds (PABs)
  - Commercial Bank Loans
- Innovative Finance Programs
  - Section 129 Loans
  - Transportation Infrastructure Finance and Innovation Act (TIFIA) credit program

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Performance Monitoring

- Pre- and Post-implementation
- Objectives and what to monitor
  - Improve mobility
    - Average speed
    - Person or vehicular throughput
    - Average travel time
    - Rates of violation per month
  - Increase travel-time reliability
    - Speed or travel-time variation
    - Transit "on-time" performance
    - Average incident clearance time

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Performance Monitoring (cont.)

- Improve safety
  - Rate of incidents by types (e.g., per month)
  - Average incident response time
- Decrease environmental impacts
  - Vehicle miles traveled
  - Fuel consumption per month
  - Monthly quantities of exhaust pollutants.
- Preservation of Revenue
  - Gross and net revenue generation
  - Operating costs
  - Revenue leakage
  - Refunds for customer service
  - Refunds for diversion into managed lanes

Next Steps

- Proceed with our work plan
  - Revise memos for Tasks 2 and 3
  - Conduct Tasks 4 and 5, which are due July 31
  - Monthly meetings with PM
  - Project presentation (temporally July 25)

Thank you!

Project Meeting, 9/2/2014

Deployment Strategies of Managed Lanes on Arterials

Today's Agenda

- Introduction: Chris Francis (5 min)
- Overview: Yafeng Yin (5 min)
- Task 4: Yafeng Yin (20 min)
- Task 5: Siriphong Lawphongpanich (20 min)

Overview

Basic Information

- Project Title
  - Deployment Strategies of Managed Lanes on Arterials
- Project Period
  - 02/11/2013 thru 11/30/2014
- Project Manager
  - Chris Francis
- Principle Investigators
  - Yafeng Yin
  - Toi Lawphongpanich

Research Objective

- Examine managed-lane deployment strategies on arterials
- Identify tools to evaluate their performances
- Explore the impacts that managed lanes on freeways have on the surrounding arterial network and the possibility for coordinated deployment and operations of managed lanes on arterials

Tasks

- Task 1: *Review of State and National Practices of Managed Lanes on Arterials*
- Task 2: *Identification and Selection of Managed Lane Strategies*
- Task 3: *Implementation and Monitoring Program*
- Task 4: *Identification of Evaluation Tools*
- Task 5: *Managed Lanes on Limited Access Facilities and Arterials*
- Task 6: *Meetings*
- Task 7: *Draft and Final Report*

Next Steps

- Revise memos for Tasks 4 and 5
- Draft final report submitted late September
- Final presentation late October
- Final report due November 30

7

Managed-Lane Strategies

- A managed-lane strategy is defined as a combination of three aspects, including the type of the managed lane, its design and implementation, and associated traffic management schemes.
  – For example, a busy-only lane can be placed on the median of a two-way arterial or is a contraflow lane at a one-way arterial. Further, various traffic management schemes, such as transit signal priority and queue jumps, may be provided to enhance its performance.

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  – Express-toll (ET) lanes
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9

Types of Managed Lanes

- Types to consider
  – High-occupancy-vehicle (HOV) lanes
  – Bus-only lanes
  ~~– Truck-only lanes~~
  – High-occupancy-toll (HOT) lanes
  – Express-toll (ET) lanes
  – Bus-toll lanes
  ~~– Truck-toll lanes~~

Toll Lanes

10

Design and Implementation

- Design and implementation of a managed lane involve six aspects:
  – Layout and placement
  – Lane length and width
  – Lane separations
  – Signs and markings
  – Access points
  – Pedestrian and bicycle conflicts

11

Traffic Management Schemes

- Various traffic management schemes can be used to enhance the performance of arterial manage lanes. They fall into one of the following three categories:
  – Intersection treatment
  – Segment management
  – Enforcement

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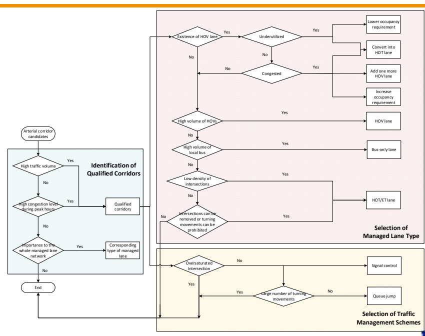
Selection and Screening Process



Task 4

Identification of Evaluation Tools

Objective

- Reviewing existing quantitative tools for evaluating various types of managed lanes
- Identifying the needs of further enhancements, if necessary

Types of Evaluation Tools

- Quite a few tools have been developed. They can be used to analyze managed lane strategies but differ in various aspects such as modeling resolution, scale and accuracy, data need and time requirement
- Sketch planning tools
  - Analyze a large set of alternatives in a quick and broad-based manner to identify a small set of the most promising alternatives for further analysis; Alternatively, they can be applied to conduct a high-level macroscopic analysis of a transportation policy in a large region

Types (Cont'd)

- Project planning tools
  - Estimate the impacts of particular projects
  - Primarily adopt the traditional four-step transportation planning process as the general methodology
- Operational planning tools
  - Further evaluate different designs of managed lanes and traffic management schemes
  - Mostly microscopic traffic simulators

Sketch Planning Tools

SMArtHOV	MOSAIC
Quick-HOV	POET-ML
Modified CRA	HOT START
SMITE-ML	SPRUCE

MOSAIC

- Sponsored by the Maryland State Highway Administration and developed by University of Maryland to evaluate the sustainability of different corridor improvement options such as HOV, HOT, ET, and bus-only lanes

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MOSAIC (Cont'd)

- In MOSAIC, a key step is to estimate the modal shift once a managed-lane strategy is implemented. The shift is captured by the following pivot point logit model:

$$P_i' = \frac{P_i \times e_i^{\Delta U_i}}{\sum_{j=1}^{k}\left(P_j \times e_j^{\Delta U_j}\right)}$$

where:

P_i': New share of using mode i;

P_i: Original share of using mode i;

ΔU_i: Change in the utility of mode i; and

k: The number of all available modes.

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MOSAIC (Cont'd)

- In the above, ΔU_i represents the utility change due to the changes in travel time and costs, i.e., $\Delta U_i = b_i \times \Delta TT_i + c_i \times \Delta Cost_i$, where ΔTT_i and $\Delta Cost_i$ represent the changes in travel time and cost, and b_i and c_i are the corresponding coefficients. The travel time is calculated by the flowing equation:

$$TT = \frac{L}{V} + nT_{wait}$$

where:

L: The length of the corridor;

V: The roadway travel speed in the corridor;

n: The number of intersections in the corridor, and

T_{wait}: Average intersection delay.

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MOSAIC (Cont'd)

Speed Estimation Based on Daily Traffic Volume per Lane (Zhang et al., 2013)

Congestion Level	Daily Traffic Volume per Lane	Speed Estimate Equation Peak Speed (mph)
Uncongested	<5500	35
Medium	5500-7000	33.58-(0.74*ADT/LANE)
Heavy	7000-8500	33.80-(0.77*ADT/LANE)
Severe	8500-10000	31.65-(0.51*ADT/LANE)
Extreme	>10000	32.57-(0.62*ADT/LANE)

Note: ADT: Average Daily Traffic, and the unit is thousand; and the lowest speed is 20 mph.

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MOSAIC (Cont'd)

Traffic Control Delay at Intersections (Zhang et al., 2013)

Congestion Level	Daily Traffic Volume per Lane	Average Delay at Intersections (Seconds per vehicle)	
		Signalized Intersections	Unsignalized Intersections
Uncongested	<5500	10	10
Medium	5500-7000	20	15
Heavy	7000-8500	35	25
Severe	8500-10000	55	35
Extreme	>10000	80	50

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MOSAIC (Cont'd)

- With the estimated travel time, MOSAIC estimates travel time reliability as follows (Ramani et al, 2008):

$$\textit{Reliability Index} = 2.189 \times (\textit{Travel Time Index} - 1) - 1.799 \times (\textit{Travel Time Index} - 1)^2$$

- Similarly, MOSAIC provides estimates of energy consumption and air pollutant emissions based on actual speeds

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POET-ML

- A sketch planning tool to quantify the impacts of potential alternative policies on existing HOV facilities
- Developed by Booz Allen Hamilton and HNTB for FHWA in 2008

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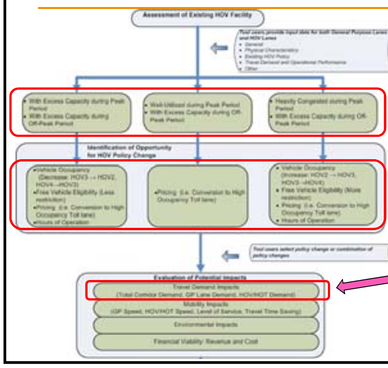
POET-ML (Cont'd)



Assess the operational performance of existing HOV facility and classify them into one of the following three conditions

Identify policy change for each condition

Estimate mode shares based on ad-hoc assumptions

POET-ML (Cont'd)

- With estimated demands, mobility impacts, such as travel speed, travel time, level of service are consequently calculated. For example, the following BPR function is adopted to estimate travel time:

$$T = T_f \times \left(1 + 0.9 \times \left(\frac{v}{c}\right)^3\right)$$

where T_f is the free-flow travel time, estimated with a free-flow speed of 65 mph; v represents traffic volume per lane per hour and c is the lane capacity.

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POET-ML (Cont'd)

- Using an average fuel consumption rate of 0.68 gallon per hour, POET-ML subsequently estimates the fuel consumption based on estimated travel times. Multiplying the fuel consumption with emission factors yields the emissions of CO, NOx and VOC.

Emission Factors (Smith et al., 2008)

Air Quality - Pollutant	Passenger Car Emission Factor
CO (kg/gallon)	14.44
NOx (kg/gallon)	1.27
VOC (kg/gallon)	1.91
Carbon Dioxide (kg/gallon)	8.79

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Evaluation

- Eight tools were identified
- Some are limited to analyzing a particular type of strategies, such as adaptation of an HOV lane to a HOT lane while others are more comprehensive
- All of them are intended to provide a quick and high-level assessment of a large set of alternatives
- Among them, MOSAIC appears the most comprehensive and is capable of evaluating different types of corridor improvements including HOV, HOT, ET, and bus-only lanes

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Evaluation (Cont'd)

- The methodology of MOSAIC is reasonable. It thus holds the most promise for being applied to evaluate arterial managed lane strategies in Florida
- Related parameters need to be recalibrated to represent the prevailing conditions in Florida. Further enhancements are needed to better capture traffic delays at intersections with different types of intersection treatments, and consider the impacts of bicycles, pedestrians, and bus stops etc.

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Project Planning

- Compared with sketch planning tools, project planning tools are more sophisticated for better capturing the characteristics of travel demand and supply and their interactions
- These tools primarily adopt the traditional four-step transportation planning process as the general methodology, with a limited number of them being activity based.

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FSUTMS

- FSUTMS consists of a standardized set of modeling steps, software programs, operating procedures and urban area data formats, which many planning models in Florida generally follow.
- We examined the modeling of each type of arterial managed lanes in the FSUTMS modeling environment

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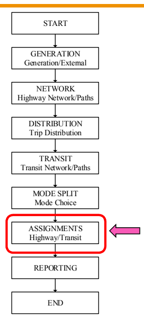
Bus-Only Lane



Note that trip assignments of transit and highway trips are separated. The impacts of bus-only lanes and the associated traffic management schemes such as queue jumps and transit signal priority can be reasonably captured in FSUTMS.

FSUTMS Transit and Highway Demand Modeling Processes (FDOT, 2012)

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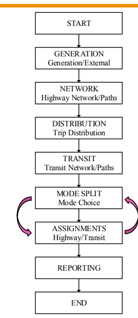
Bus-Only Lane (Cont'd)



Iterations between mode split and traffic/transit assignments will be needed to capture the mode shift and the change in traffic conditions caused by the deployment of bus-only lane strategies.

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HOT Lane

- Yin et al. (2007) summarized three procedures that have been applied or proposed to model HOT lanes in a traditional four-step modeling process
  - Modal-split procedure
  - Deterministic or stochastic traffic assignment
  - Post processor

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HOT Lane (Cont'd)

Southeast Florida Travel Time Values by Travel Demand Model Trip Purpose (The Corradino Group, Inc. and Cambridge Systematics, Inc., 2009)

Market	Value (2004 Dollars)
Home-Based Work	$12.69 per hour
Home-Based Shopping	$10.59 per hour
Home-Based School	$10.58 per hour
Home-Based Social/Recreational	$10.59 per hour
Home-Based Other	$12.10 per hour
Home-Based Unknown	$11.34 per hour
Non-Home-Based	$12.10 per hour

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HOT Lane (Cont'd)

- **A combined mode split/traffic assignment procedure (Parsons Brinckerhoff, 2012)**
  - **At each iteration of the assignment procedure, for each O-D pair, the travel time difference between vehicles using any segment of managed lanes and those without accessing managed lane will be calculated and compared to the total amount of toll paid. The ratio between the toll and travel time saving is compared against *the willingness to pay table* to determine the proportion of the O-D demand that will not use managed lanes for sure. The remaining portion may use the lanes if they are found to be preferable in the assignment.**

HOT Lane (Cont'd)

Willing to Pay Proportion for Cost per Time Saved, by Demand Category (Parsons Brinckerhoff, 2012)

Toll Cents per Minute Saved	Demand Category							
	1	2	3	4	5	6	7	8
0	95	95	95	95	95	95	95	95
8	50	50	50	50	50	50	50	50
10	40	40	40	40	40	40	40	40
16.3	25	25	25	25	25	25	25	25
20	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3
23.7	15	15	15	15	15	15	15	15
31.4	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
41.7	5	5	5	5	5	5	5	5
51.8	4	4	4	4	4	4	4	4
58.3	2	2	2	2	2	2	2	2
66.7	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Demand Categories:
1 - urban & rural short
2 - Long-Distance Business
3 - Long-Distance Tourist
4 - Short, Cross-border EI
5 - Long-Distance US, Canada
6 - Medium Trucks
7 - Unused
8 - Light Trucks

Evaluation

- **FSUTMS can reasonably accommodate and evaluate different managed-lane strategies.**
- **There are some elements that potentially lead a traditional four-step procedure to offer erroneous forecasts. However, these shortcomings are not unique to analysis of managed lane strategies, but also other problems like emerging policy issues and mobility options.**
- **Although activity-based models show promise for analyzing managed lane strategies in an integrated way, they are much more complex and require more resources to implement.**

Recommendations

- **To better model arterial managed-lane strategies, future research is needed to enhance link performance functions to capture the impacts of different intersection treatments, e.g., queue jumps, signal priority, turning movement management, on intersection delays and link travel times.**
- **To adequately capture the impacts of bus-only lanes on other regular vehicles and more accurately predict the mode shift from highway to transit, a multimodal traffic assignment model can be applied in FSUTMS, which, however, substantially changes its transit modeling process.**

Operational Planning

- **The analysis based on either a sketch or project planning tool is not sufficient for supporting the design and operations of a managed-lane facility, as the tools do not adequately model traffic dynamics and fail to capture complex interactions among a large set of design and operation variables**

Operational Planning (Cont'd)

- **Very often, operational planning tools are microscopic traffic simulators such as VISSIM, Paramics, CORSIM and SimTraffic**
- **Among them, some consider VISSIM as the most appropriate tool to model managed lanes (Fenno et al., 2002). On the other hand, a team at University of Florida has enhanced CORSIM and made it a tool particularly useful for simulating the operations of HOT lanes (Michalaka et al., 2012)**

CORSIM

- CORSIM is a widely-used microscopic traffic simulation software, originally developed by FHWA. It is now maintained, developed and distributed by McTrans at the University of Florida
- To simulate HOT lane operations, three modules were developed by Michalaka et al. (2012), including dynamic tolling algorithms, toll structures for a HOT facility with multiple tolling segments, and modeling lane-choice behaviors of drivers between HOT and GP lanes

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CORSIM (Cont'd)

- Tolling algorithms
  - Traffic-responsive pricing
  - Closed-loop control
  - Time-of-day pricing
- Lane choice
  - Simple decision rules
- Toll structures
  - Zone-based
  - Origin-based
  - Distance-based
  - Origin-destination-based

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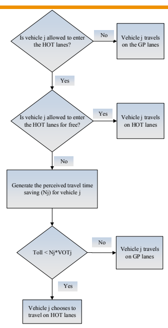
Lane Choice



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Evaluation

- Existing operational planning tools are capable of conducting sophisticated analysis for various types and designs of arterial managed lane strategies.
- Among them, the enhanced CORSIM provides unique feature and functionality of simulating different types of toll lanes while VISSIM is a promising tool for simulating strategies related to bus-only lanes with advanced traffic signal control.

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Thank you!

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Task 5:
Managed Lanes on Limited Access Facilities and Arterials

1

Task's objective

- To explore the impacts that managed lanes on limited access facilities have on
  - The surrounding arterial network and
  - The possibility for coordinated deployment and operations of managed lanes on arterials.

2

Reminder

- Task 2: Identification and Selection of Managed Lane Strategies
  - Types of Arterial Managed Lanes
    - HOV, HOT, Bus-Only, Express-Toll & Bus-Toll Lanes
  - Design and Implementation of Managed Lanes
    - Layout and placement, lane length and width, lane separations, sign and markings, access points, pedestrian and bicycle conflicts
  - Traffic Management Schemes
    - Intersection treatment (e.g., queue jumps, segment management, and enforcement
  - Selection and Screening Process Flowchart

3

Reminder (cont.)

- Task 3: Implementation and Monitoring Program
  - Planning
    - Include in MPO's long-range Metropolitan Transportation Plan (MTP) and Transportation Improvement Program (TIP)
  - Design and Procurement
    - Secure funding, complete design work, and put projects out for bids.
  - Construction
  - Operation and Maintenance
  - Public Outreach

4

Assumptions for Task 5

- Managed-lane projects for the impact study
  - Projects have been screened and selected as a part of the Congestion Management Process (CMP).
  - Included in long-range Metropolitan Transportation Plan (MTP) and Transportation Improvement Program (TIP)
  - Projects in the collection are physically feasible and interoperable with facilities in a network
    - Access policy, pricing plan and collection systems
    - Physical feasibility at, e.g, access points and intersections.

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Assumptions for Task 5 (cont.)

- Improvements for each project quantified.
  - Change in travel speed due to, e.g., grade-separated queue jumps at selected intersections, change in speed limit, turning movement management, and signal timing/priority.
  - Number of additional lanes
  - Pricing scheme
  - Access policy, e.g., HOV 2+ or 3+

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Our approach

- Estimate the impact of travel delay.
  - Compare delay before and after project implementation.
    - Several projects can be considered together to take into account the synergist effects.
- Use multi-modal equilibrium model
  - Project improvements lead to different model parameters.
  - Assume that travelers always choose a least-cost route.
    - Travel cost (time) increases when many choose to travel on the same road or highway.
  - Equilibrium is reached when no one has any (cost) incentive to switch routes.
    - Travel delay is calculated from equilibrium flows.

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Example: Area of Study

- Area of study

8

Example: Area of Study (cont.)

- Facility selected for our example

Table 3-1: Facility-Type Code for Freeways and Arterials

Facility-type Code	Explanation
11	Freeway Segments
12	Freeway Segments
21	Uninterrupted Segments
41	Higher Speed Interrupted Facility
61	Lower Speed Facility and Collector
81	2+ HOV Segments
91	Toll Freeway Segment

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Example: Area of Study (cont.)

- Resulting network

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Example: Area of Study (cont.)

- Our representation

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Example: Managed Lanes Projects

- Schemes
  - Adding a managed lane to East-West links.
  - Converting a lane on North-South links into a managed lane.

Table 3-3: Links for Managed-Lane Consideration

Scheme	Links for consideration	Corresponding Arterials
East-West	(3,30), (31,5), (32, 82), (82,6), (33, 8), (34,9), (35,10), (53, 33), (56,11), (57,12),	SR 98, 812, 804, 806, 808, 869, 814, 816
North-South	(52,53), (53,54), (54, 55), (55,56), (56, 57), (57,58)	US441 from SR804 to 595
Both	All of the above	All of the above

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Example: Managed Lanes Projects (cont.)

- **Assumptions**
  - 10% of OD demands are HOV's
  - Toll rate on all toll roads is $0.05 per mile.
  - The average value of time is $32 per hour.
  - Converting a GP lane into a managed lane (HOV or HOT) increases the travel time by 5 mph.

Results: Adding/Converting to HOV Lanes

Table 3-4: Reduction in Travel Delay Due to Adding and Converting to HOV Lanes

Switch to Carpool	East-West Delay (days)	East-West Reduction	North-South Delay (days)	North-South Reduction	Both Delay (days)	Both Reduction
5%	186.01	4%	187.04	4%	186.87	4%
10%	178.61	8%	178.76	8%	179.24	8%
15%	172.10	11%	172.23	11%	172.42	11%
20%	166.24	14%	166.35	14%	166.35	14%
25%	160.83	17%	160.85	17%	160.76	17%

- **Reduction in delay is not additive.**

Results: Adding/Converting to HOV Lanes (cont.)

Table 3-5: Utilization of New HOV Lanes Under the East-West Scheme

Tail	Head	Cap. (Veh./Hr)	Flow (veh./hr)	V/C
3	30	900	357.91	0.40
5	31	910	69.35	0.08
6	82	910	266.13	0.29
8	33	910	260.27	0.29
9	34	900	92.34	0.10
10	35	910	717.81	0.79
11	56	910	64.08	0.07
12	57	910		
30	3	900	417.15	0.46
31	5	910		
32	82	910	344.15	0.38
33	8	910	319.75	0.35
34	9	900		
35	10	910	765.77	0.84
56	11	910	109.65	0.12
57	12	910		

- **Lanes with low utilization are candidates for elimination**

Results: Adding/Converting to HOT Lanes

Table 3-6: Changes in Travel Delay and Toll Revenue From Adding and Converting to HOT Lanes

Switch to Carpool	East-West Delay (days)	East-West Reduc.	East-West Toll Rev. ($1000)	North-South Delay	North-South Reduc.	North-South Toll Rev. ($1000)	Both Delay (days)	Both Reduc.	Both Toll Rev. ($1000)
5%	166.99	14%	1.30	167.78	14%	1.25	166.54	14%	1.36
10%	161.75	17%	1.21	162.34	16%	1.17	161.28	17%	1.26
15%	156.84	19%	1.12	157.18	19%	1.08	156.26	20%	1.17
20%	152.24	22%	1.04	152.41	22%	0.99	151.65	22%	1.07
25%	147.52	24%	0.97	147.84	24%	0.91	147.08	24%	0.99

- **Toll revenue is per hour.**
- **Toll revenue decreases as % switched to carpools increases.**
- **When compared to HOV lanes, HOT lanes lead to larger reduction in travel delay.**
  - At 5% switching rate, 4% for HOV versus 14% for HOT.

Results: 25% Demand Increase and HOT

Table 3-8: Changes in Travel Delay and Toll Revenue From Adding and Converting to HOT Lanes with higher demands

Switch to Carpool	East-West Delay	East-West Reduc.	East-West Toll Rev. ($1000)	North-South Delay	North-South Reduc.	North-South Toll Rev. ($1000)	Both Delay	Both Reduc.	Both Toll Rev. ($1000)
0.05	226.77	16%	1.64	226.59	16%	1.61	224.21	17%	1.74
0.10	218.40	19%	1.52	218.35	19%	1.49	216.29	20%	1.62
0.15	210.40	22%	1.41	210.51	22%	1.38	208.77	23%	1.50
0.20	203.05	25%	1.30	203.00	25%	1.28	201.63	26%	1.39
0.25	196.13	28%	1.18	196.04	28%	1.17	194.95	28%	1.27

- **25% Demand increase leads slightly larger reduction in travel delay.**
- **Combining East-West and North-South Scheme leads to slightly higher reduction in travel delay.**

Conclusions

- **Propose a model that can be used to estimate in the impacts of managed lanes.**
- **Example**
  - Network of highways and arterials from Districts 4 and 6.
  - Estimate impacts on travel delay using three schemes
    - East-West, North-South, and both.

Thank you!

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