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16. Abstract <p>Transportation agencies around the nation find themselves pushing the envelope of innovation to keep up with congestion caused by exploding demand for limited roadway space. Managed lanes provide a mechanism for harnessing the potential of the current infrastructure. Special-purpose lanes, including high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes, allow engineers to manipulate roadway parameters to achieve varying levels of service.</p> <p>Managed lanes are controlled access facilities, and must somehow be separated from general-purpose lanes. One principle question that must be asked is what type of delineation technique should be used? What are the properties of different delineators that make some more favorable than others? How do roadway characteristics, such as available width and traffic volume, factor into the choice of delineation? Much has been written on the safety and cost aspects of different delineation techniques used for HOV lanes; are these analyses applicable to other managed lanes as well? What about the other characteristics of the techniques: what are they, and how important are they to the choice of delineation? This report addresses some of these questions and sheds some light on their ultimate answers.</p> <p>Three basic categories of delineation exist: concrete barriers, pylon posts, and painted buffers. This research project assembled an expert panel to gather a collective knowledge of factors involved in the choice of delineation most appropriate to given scenarios. The summary of this panel's discussions, included in this report, will serve as a useful guideline for engineers looking to choose the best type of delineation for future, successful managed lane projects.</p>					
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## **Best Practices: Separation Devices between Toll Lanes and Free Lanes**

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## **Products**

Chapter 4 of this document represents Product 1, Recommendations for Separation of Toll and Free Lanes.

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# Chapter 1. Study Objectives and Achievements

## 1.1 Introduction

Transportation agencies around the nation find themselves pushing the envelope of innovation to keep up with congestion caused by exploding demand for limited roadway space. Simply continuing to build new highway lanes is proving unfeasible; instead, using the existing infrastructure in new and inventive ways holds great promise for efficiently addressing the problems at hand. Managed lanes provide such a mechanism for harnessing the potential of the current infrastructure. These special-purpose lanes, which include high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes, allow adept engineers to manipulate roadway parameters to achieve varying levels of service, vehicle compositions, and driver behaviors. Table 1.1 lists the number of such projects underway nationwide.

**Table 1.1: Number of Managed-Lane Projects by State/Province**

<b>State</b>	<b>No. of Projects</b>
California	47
Colorado	2
Connecticut	1
Florida	5
Georgia	10
Maryland	7
Massachusetts	6
Minnesota	1
New Hampshire	1
New York	2
North Carolina	7
Pennsylvania	1
Tennessee	1
Texas	14
Utah	1
Virginia	4
Washington	8
Toronto/Mississauga, Canada	1
<b>Total</b>	<b>119</b>

Source: [http://ops.fhwq.dot.gov/Travel/traffic/managed\\_lanes/index.htm](http://ops.fhwq.dot.gov/Travel/traffic/managed_lanes/index.htm)

HOV lanes have been used for decades, and a great deal of literature chronicles experiences with them; however, HOT lanes are a much newer innovation, and the knowledge base dealing with them is significantly smaller. Because managed lanes, including HOT lanes, are controlled-access facilities and must somehow be separated from general-purpose lanes, several key questions must be asked. Principally, what type of delineation technique should be

used? What are the properties of different delineators that make some more favorable than others? How do roadway characteristics, such as available width and traffic volume, factor into the choice of delineation? Much has been written on the safety and cost aspects of different delineation techniques used for HOV lanes; are these analyses applicable to other managed lanes as well? What about the other characteristics of the techniques: what are they, and how important are they to the choice of delineation? This work will begin to address some of these questions and shed some early light on their ultimate answers.

## 1.2 Background Information

Though the specifics of delineating managed lanes are numerous and allow for a wide variety of possible implementations, most delineation techniques used today fall within three broad families: concrete barriers, painted buffers, and plastic posts. The discussion that follows describes basic defining characteristics of these delineation families, different subgroups within each family, and examples of the usage of each family in managed lane facilities around the United States.

### Pavement Markings

Simple painted buffers have been the most widely used technique for delineating HOV lanes from other freeway lanes (Figure 1.1). Pavement markings are simple to install, inexpensive, and blend well aesthetically with the markings between other lanes, so the consideration of using them for HOV and other managed lanes is natural and logical.



*Figure 1.1: Buffer-separated HOV lanes in Vancouver*

Source: <http://www.rtc.wa.gov/hov/links.htm>

Buffer systems range from several feet wide, sometimes over 12 ft wide, to nothing more than a single paint stripe that looks no different from the separation between two general-purpose lanes. The buffer may utilize rumble strips or it may be raised like a curb in order to discourage illegal crossing. Different arrangements can provide benefits and drawbacks; a 12-ft buffer, for

example, requires a significant amount of right-of-way but can be used as an acceleration/deceleration lane to mitigate conflicts resulting from speed differentials.

Currently, few managed lane projects other than HOV lanes utilize pavement markings or buffers to separate the managed lanes from the general-purpose. However, in early 2005, Interstate 394 HOT lanes began operation in Minneapolis, Minnesota (1). These HOT lanes, converted from an HOV lane system, are largely striped buffer-separated. The I-394 project should provide a wealth of information in the near future on enforcing access restrictions and toll evasion for pavement marking-separated HOT lane facilities.

Current pavement marking-separated HOV lanes throughout the country, including Vancouver, WA and Portland, OR, experience violation rates of 10-15 percent, which are consistent with the national average HOV violation rate (2). While this result provides an encouraging portrayal of buffer-separation violations, this rate may not be applicable when the added motivation of toll evasion is introduced with HOT lanes. Because of this additional motivation for violation, the I-394 HOT lanes and future HOT lanes on I-680 in Alameda County, California (3) and State Route (SR) 167 in Washington (source: <http://www.wsdot.wa.gov/Projects/SR167/HOTLanes>) could provide valuable information on the effectiveness of using pavement markings to separate HOT lanes.

### Post Delineators

The post-delineation family takes a paint-striped buffer and adds a series of plastic pylon posts to discourage illegal crossings (Figure 1.2). In many senses, post delineation is a subcategory of buffer, as posts and buffers share many of the issues and advantages. However, because posts utilize a form of physical barrier that drivers are unlikely to cross, they also share many characteristics with concrete barriers.



Figure 1.2: Post-separated HOT facility on SR 91 in California

Original source: <http://www.wilbursmith.com/Services.cfm?s=152>

Perhaps the most well known managed facility to utilize plastic posts is SR 91 in Orange County, California. SR 91, a pioneering effort in congestion pricing in the U.S., is a 10-mile long express lane system composed of two lanes in each direction with no intermediate access (3). The posts used to delineate SR 91 and other, similar facilities can *break away* and thus require substantial maintenance costs. Traditional pylon configurations require 10 percent of the delineators to be replaced every 60 to 90 days, resulting in nearly all of the delineators needing replacement each year (4). Additionally, when knocked over, post delineators become roadway debris, introducing a possible safety concern.

### *Retractable Delineators*

A sub-category of delineator-separated managed lanes has recently arisen to address issues at electronic tolling stations. When reversible lanes are part of a managed lane strategy, tolling plazas often require delineator configuration changes to accommodate the direction of traffic flow. Because electronic tolling allows vehicles to pass through tolling stations at high speeds, Florida is considering retractable delineators at its tolling plazas to increase safety for workers at the tolling station (5). The retractable delineators will eliminate the need for employees to manually change delineator configurations at the plaza. Retractable delineators are currently being used in San Clemente, CA on I-5 and on the New York Thruway near Albany (4).

In managed lane strategies that would incorporate reversible lanes or strategies, the potential benefits of retractable delineators are apparent. However, their high initial construction costs and maintenance issues must be considered whenever this type of delineation may be used for managed lane projects.

### **Barriers**

The majority of current and planned managed lane projects involving some form of tolling and/or congestion pricing use continuous concrete barriers for lane separation (Figure 1.3). Currently, the I-15 FasTrak Express Lanes in San Diego, CA, the I-10 and US 290 QuickRide Lanes in Houston, and the New Jersey Turnpike Dual-Dual Section utilize concrete barriers to separate managed and main lanes. Barriers have the obvious benefit of maintaining the lowest violation rate because they do not allow vehicles to access managed lanes at intermediate points.



*Figure 1.3: Barrier separation in Houston*

Source: <http://ops.fhwa.dot.gov/docs/Houston/index.htm>

### *Moveable Barriers*

An extension of barrier separation is a technology developed for contraflow HOV lanes: movable barriers. Movable barriers are in operation in at least fifteen different locations worldwide, including Texas, Pennsylvania, Puerto Rico, New Zealand, and Hawaii. This unique form of delineation utilizes a large vehicle that moves along a stretch of lanes, taking in special barriers from one side and placing them on the other (Figure 1.4). The movable barrier system

lends itself nicely to a contraflow setup because it provides the safety inherent to barrier delineation while still allowing sufficient flexibility to alter lane configurations.

While movable barriers definitely provide an exciting technology, their application is likely to be limited by their considerable initial and operational costs. Nevertheless, if contraflow lanes are to be considered as part of a managed lane strategy, movable barriers provide a potentially desirable alternative.



*Figure 1.4: Moveable barrier separation in Hawaii*

Source: <http://www.barriersystemsinc.com/success/story.asp?key=67>

## Delineator Costs

Design details of the members of each of these families are variable; for example, buffer widths range from 8 in. to several feet, and *post type* delineators even include several *pop up* systems. The choice of the *best* separator device for a given application depends on many factors, including available cross section spaces, initial costs, maintenance costs, enforcement techniques, enforcement efforts available, and desired compliance levels. Rough price data for the initial cost of different system types is included in Table 1.2.

**Table 1.2: Cost Data for Various Delineators**

	Avg (price/ft)	Price per mile
Concrete Barrier	\$37.60	\$198,539
Stripe (4")	\$0.26	\$1,365
Stripe (8")	\$0.61	\$3,199
Stripe (12")*	\$4.21	\$22,245
Stripe (24")*	\$7.22	\$38,146
Pylons (each)**	\$29.33	\$7,743
Retractable Pylons (each)***	\$3125	\$825,000

\*12" and 24" stripe prices taken from projects with small quantities of those widths; prices likely lower when wide stripes represent larger fraction of project materials

\*\*Data from California DOT, for "Channelizer (Surface Mounted)"; 20 ft spacing assumed.

\*\*\*Data from the FHWA's *A Guide for HOT Lane Development* (4); 20 ft spacing assumed

### 1.3 Literature Review

As previously mentioned, the amount of existing information on a given type of managed lane depends on the type of facility in question. There is a wealth of literature addressing safety and cost aspects of HOV lanes, but the applicability of this information to HOT lanes and other managed lanes is not always clear. Furthermore, there is very little information on characteristics of delineation techniques outside of cost and safety for any type of managed facility.

The Federal Highway Administration's (FHWA) *A Guide for HOT Lane Development* has a chapter dedicated to HOT lane development, installation, and maintenance, including a section discussing delineation strategies (4). The *Guide* prefers physical separation, such as posts or concrete barriers, to pavement marking because of its superior ability to provide access control, reduce violations, and maintain improved service and safety. The key safety issue attributed to pavement markings is the ability of a driver to swerve into the juxtaposed lane, which may be moving at a different speed. Comparing posts and barriers, posts are less expensive to install, require less right-of-way, and allow easier access to the managed lane for emergency vehicles. However, barriers have much lower maintenance costs and tend to enhance safety for users of both the managed lanes and the general-purpose lanes. Barriers are also essential if reversible-flow lanes are used.

The Texas Transportation Institute (TTI) looked at crash data for buffer- and barrier-delineated facilities in Dallas before and after HOV implementation (7). The researchers found significant accident rate increases for buffer-delineated facilities, primarily in the HOV lane and adjacent general-purpose lane. Buffer-delineated facilities were also associated with higher rates of injury accidents because of high-speed differentials between HOV lanes and adjacent general-purpose lanes. Furthermore, the researchers found that the high-speed differential posed a problem for merges into and out of the HOV lane. Barriers were not found to introduce any significant safety issues, although the researchers found that the access points to barrier-separated facilities could become a catalyst for incidents.

A number of studies have looked at the safety of concurrent HOV lanes using a paint stripe separation with less than 2 ft of buffer width. A report produced for the 1997 ASCE conference title, *Traffic Congestion and Traffic Safety in the 21<sup>st</sup> Century: Challenges, Innovations, and Opportunities*, stated that adding general-purpose lanes to a facility can reduce accidents by about 29 percent on average (8). However, adding a concurrent HOV lane does not produce a similar improvement, and in many cases, actually increases the likelihood of accidents. A high-speed differential between the two types of traffic is cited as a reasonable cause. The report had insufficient evidence for wider buffers or for concrete barriers, but the majority of the data showed narrow buffers may be troublesome with differing traffic speeds.

A feasibility study for HOT lanes in Santa Cruz, CA, by Wilbur Smith Associates, introduces a process for determining the best type of facility for a current freeway alignment (9). The need for a HOT facility arises from the desire to increase passenger movement on a congested freeway and to provide a high-speed option for users willing to pay for the convenience. While the study focuses on Highway 1 in Santa Cruz, it demonstrates some of the decisions and considerations that factor into the design of a HOT facility. For example, a transportation agency may wish to know whether the toll revenues will balance the costs of adding necessary lanes and equipment. Physical characteristics also play a role in possible alternatives; for example, Wilbur Smith suggests that concrete barriers would be the safest method for separating a reversible facility from general-purpose lanes on a highway.



The *High-Occupancy Vehicle Guidelines for Planning, Design and Operations*, prepared for the California Department of Transportation (CALTRANS), is another resource that, though written with HOV lanes in mind, can be used to aid in the design of all types of managed lanes (10). The report asserts that barrier facilities are operationally advantageous to buffered facilities because of their ease of enforcement, low violation rates, and protection for HOT lane users from traffic and incidents in the general-purpose lanes. Barrier drawbacks include higher cost and the requirement for wider right-of-way. Contiguous facilities—that is, facilities utilizing paint stripes with zero-width buffers—can be a good choice when right-of-way is limited, though the close quarters and speed differential may lower the level of service. Additionally, contiguous facilities can be easily converted to a general-purpose lane during off-peak times. Wide buffers of at least 12 ft are a good compromise between contiguous and barrier facilities, because they provide both excellent separation of traffic and space for potential acceleration and deceleration lanes for weaving between the managed lanes and general-purpose lanes.

## **1.4 Summary**

The current state of research on managed lanes leaves many important questions unanswered, but managed lanes, particularly HOV lanes, have been around for many years regardless of this relative lack of information. Many transportation agencies originally asked themselves these same questions and, finding that the existing answers were generally lacking in thoroughness, decided to fearlessly plunge into the world of managed lanes anyway and answer these questions. This project hopes to gain a better understanding of managed lane delineation from the experience of these individuals, so that the hard work and patience they exercised in implementing their managed lane projects can help make other similar projects successful.



## Chapter 2. Expert Panel

A primary goal of this study was to construct a panel of individuals from around the U.S. with experience with managed lanes to discuss the considerations for choosing delineation strategies for managed lanes.

### 2.1 Panel Discussion

#### Structure

The goal of the expert panel was to initiate a wide-ranging discussion on all conceivable factors that may influence the choice of a technique for delineating managed lanes. Many possible structures for the discussion were considered; the final arrangement brought the panelists together with a moderator, Jay Nelson, retired Texas Department of Transportation (TxDOT) District Engineer for Dallas, to guide the talks.

Discussion of the delineation techniques occurred in two steps: first, panelists considered the implications of different roadway conditions on the choice of delineation. Specifically, they were asked the question: “If this condition were present, would this delineation technique be acceptable?” and answered with “yes” (barring other complications, the technique would suffice under this scenario), “no” (the technique will never be acceptable under this scenario), or “maybe” (there are other factors that may negate conflicts derived from this condition). More important than the simple answer is the exchange of ideas and reasoning that inspired the answer; these were recorded and are summarized in this chapter. The panelists were given the opportunity, prior to the discussion, to add to or subtract from the list of roadway conditions that the researchers had previously brainstormed. The final list of roadway variables considered were lane and shoulder widths, traffic volume on the highway, truck volume on the managed lanes, bus volume on the managed lanes, centerline geometry, and main lane entry/exit frequency.

Second, panelists considered characteristics inherent to each type of delineation technique that would not vary from site to site. They were asked to determine whether the inherent characteristics for each delineation style posed any particular disadvantage for that style compared to the others. The panel was able to add to or subtract from the list of technique-specific characteristics and develop a final list of common characteristics; that final list was composed of entry/exit considerations, enforceability/compliance, cost, safety, aesthetics, and constructability.

### 2.2 Panel Participants

The individuals who participated as Expert Panel members included:

Mark Leth—Washington State’s Northwest Region Traffic Engineer. Mr. Leth’s office manages Washington State’s HOV system and is also in charge of establishing HOV signing and marking policy.

William B. Finger—Assistant Transportation Director (retired), Charlotte Department of Transportation; member, Transportation Research Board (TRB) Committee on HOV Systems. Mr. Finger has participated in several discussions on HOV/HOT lanes and is a main contact for information on North Carolina’s HOV system.

Dawn Helou—Senior Transportation Engineer, Transportation Management / HOV Operations, Caltrans District 7, Los Angeles; Ms. Helou is in charge of HOV operations, call boxes and traffic monitoring for the Los Angeles area.

Sunil Taori—Transportation Engineer, Virginia Department of Transportation. Mr. Taori has participated in several HOV discussions and committees and has done work on several HOV research projects.

Joe El Harake—Caltrans District 12 HOV coordinator.

Jay Nelson—Retired TxDOT Dallas District Engineer; Mr. Nelson oversaw the construction of an extensive HOV lane network in Dallas. He served as moderator for the expert panel.

Melanie Young—Transportation Operations Engineer, TxDOT Dallas District.

Joseph Carrizales—TxDOT Project Director for this study and TxDOT Austin District's Advanced Project Development Engineer.

## **2.3 Results**

Two information sources were used to assess and decipher the expert panel discussions: the questionnaires regarding each family of delineation devices that requested *yes-no-maybe* responses to questions about delineation device application and an audio recording of the entire discussion. The questionnaires were used both as a tool to guide the conversation and as a method of generally gauging the appropriateness of different delineation techniques under myriad scenarios. The audio recording was analyzed in depth to fully understand the reasoning behind the choices made by the panel in filling out the *yes-no-maybe* chart. Results are included in Table 2.1, an updated version of the chart appended with abbreviated considerations for each point of analysis for each delineation technique. An extended version of the considerations follows the table.

**Table 2.1: Expert Panel Results**

**Site Characteristic Considerations**

Responses indicate the panel's opinion about the use of this delineation family under each of the following conditions:

	Concrete Barrier	Buffer	Post
<b>I. Lane &amp; Shoulder Width</b>			
<b>1. Ideal lane and shoulder widths</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>2. Lane and shoulder widths less than ideal</b>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Must have room for the barrier itself.</li> <li>– Must have sufficient room in a managed lane delineated by barriers to allow incident bypass and clearing.</li> <li>– <i>Tunnel effect</i>: Users of managed lane may feel they have less room than they actually do; Level of Service may drop.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Drivers will be less likely to maintain a high speed differential on a narrow lane; Level of Service may drop.</li> <li>– Unlawfully crossing boundary will be easier.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Posts require a buffer of at least 2 ft.</li> <li>– Drivers will be less likely to maintain a high speed differential on a narrow lane; Level of Service may drop.</li> <li>– Unlawfully crossing boundary will be easier.</li> <li>– Posts may make users of managed lane feel like they have less room than they actually do; Level of Service may drop.</li> </ul>
<b>3. Shoulders available in managed lane</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>4. No or minimal shoulder available in managed lane</b>	<b>No</b> <ul style="list-style-type: none"> <li>– Motorists can be trapped behind an incident.</li> <li>– No room to safely avoid a disabled vehicle.</li> <li>– Emergency vehicles may not be able to reach an accident.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– No refuge for disabled vehicles.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– No refuge for disabled vehicles.</li> </ul>
<b>II. Traffic Considerations</b>			
<b>1. Uncongested main lanes</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>2. Congested main lanes</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Physical barrier separates managed lane and main lanes, making higher speed differentials possible.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Drivers may be uncomfortable with high speed differentials without physical separation.</li> <li>– Risk of drivers illegally swerving into managed lanes to pass slower traffic.</li> <li>! A wide buffer may negate these effects.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Drivers may be uncomfortable with high speed differentials without a more rigid separation</li> <li>! A wide buffer may negate these effects.</li> </ul>

	Concrete Barrier	Buffer	Post
<b>3. Trucks allowed in managed lane</b>	<b>Yes</b> + General-purpose lanes are protected from trucks using the faster managed facility. – If managed lane consists of only one lane, drivers may get stuck behind trucks, especially on inclines.	<b>No</b> – Having trucks in the fast-moving managed lanes without any physical separation from slower main lanes is undesirable.	<b>No</b> – Having trucks in the fast-moving managed lanes without more substantial physical separation from slower main lanes is undesirable. – Trucks often mow down posts, especially in restricted-width conditions.
<b>4. Trucks in adjacent general-purpose lane</b>	<b>Yes</b> + Provides protection for managed lane from adjacent, slow-moving trucks.	<b>Maybe</b> – No protection for managed lane from adjacent, slow-moving trucks.	<b>Maybe</b> – No protection for managed lane from adjacent, slow-moving trucks.
<b>5. Buses/transit use managed lane</b>	<b>Yes</b> ! Slow-moving buses may lower the Level of Service for the facility if a single-lane configuration is used.	<b>Yes</b> ! Slow moving buses may encourage people to weave in and out of managed lanes to overtake them.	<b>Yes</b> ! Slow-moving buses may lower the Level of Service for the facility if a single-lane configuration is used.
<b>6. No buses on managed lane</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>III. Centerline Geometry</b>			
<b>1. Less than ideal horizontal curve radii</b>	<b>Maybe</b> – If sight distance is less than ideal, barriers may further reduce it. ! Adequate shoulders are essential: if not provided, vehicles will be forced to drive close to the barrier; level of service may suffer, especially on turns. ! Adequate shoulders will allow drivers to swerve to avoid incidents that they were blocked from seeing.	<b>Maybe</b> – Drivers may feel uncomfortable making a sharp turn coupled with a high-speed differential.	<b>Maybe</b> – Drivers may feel uncomfortable making a sharp turn with a high-speed differential. – Posts may provide a distraction, which may increase stopping sight distance.
<b>2. Ideal horizontal curve radii</b>	<b>Yes</b>	<b>Yes</b>	<b>Maybe</b> – Use of posts on curves can be expected to increase maintenance costs due to vehicle impacts

	Concrete Barrier	Buffer	Post
<b>3. Steep grades and/or short vertical curves</b>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ In cases of congested main lanes, main lanes will be protected from drivers swerving to avoid an incident in the managed lane.</li> <li>– If sight distance is less than ideal, barriers may further reduce it.</li> <li>– In cases of uncongested main lanes, drivers are unable to swerve into clear main lanes to avoid incidents they couldn't see. Adequate shoulders in the managed lane will help.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ Drivers have the ability to swerve into a clear main lane to avoid an incident on the managed lane.</li> <li>– With reduced sight distance, drivers may be forced to swerve into main lanes to avoid an incident they couldn't see.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ Drivers have the ability to swerve into a clear main lane to avoid an incident on the managed lane.</li> <li>– Posts may provide a distraction and increase stopping sight distance.</li> <li>– With reduced sight distance, drivers may be forced to swerve into main lane traffic to avoid an incident they couldn't see.</li> </ul>
<b>4. Ideal vertical alignment</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>IV. Freeway Main Lane Entry/Exit Considerations</b>			
<b>1. Frequent entry/exit ramps</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ If direct connections to the managed facility are used, frequency of ramps will not affect operations.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Having frequent ramps requires frequent weaving to move from the ramp to the managed lane.</li> <li>– If there are left-side exits, drivers may illegally queue up in the managed lane to access the exit.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– Having frequent ramps requires frequent weaving to move from the ramp to the managed lane.</li> <li>– If there are left-side exits, drivers may illegally queue up in the managed lane to access the exit.</li> </ul>
<b>2. Infrequent entry/exit ramps</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ If direct connections to the managed facility are used, frequency of ramps should not effect operations.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– With less frequent ramps, there is a higher quantity of weaves for each ramp.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>– With less frequent ramps, there is a higher quantity of weaves for each ramp.</li> </ul>

#### **Delineation Device Specific Considerations**

Responses indicate whether or not the panel believe that the delineation device can be used without worry of problems arising because of the following considerations:

<b>V. Managed Lane Entry/Exit Considerations</b>			
<b>1. Entry/exit operation</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Direct connections function identically to regular exit ramps.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Sufficient distance must be given to accelerate or decelerate to match speed of destination lane.</li> <li>– Requires weaving movement to enter/exit facility.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Sufficient distance must be given to accelerate or decelerate to match speed of destination lane.</li> <li>– Requires weaving movement to enter/exit facility.</li> <li>– Drivers may strike posts while entering managed lane.</li> </ul>

	Concrete Barrier	Buffer	Post
<b>2. Entry/exit accessibility and utilization</b>	<b>No</b> <ul style="list-style-type: none"> <li>+ Access can be controlled with barriers.</li> <li>– When direct connections are used, drivers must find the location of entrance.</li> <li>– With direct connections, there will be fewer access points because of related costs.</li> <li>– Changing access points is very difficult.</li> </ul>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Accessing facility is as simple as merging to another lane (which can be continuous or at discrete locations).</li> <li>+ Changing access points is simple.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ Accessing facility is as simple as merging to another lane, though only at discrete locations where posts are temporarily dropped.</li> <li>+ Changing access points is relatively easy.</li> </ul>
<b>VI. Compliance Issues</b>			
<b>1. Strict compliance is desired</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Drivers cannot, even temporarily, access facility illegally (if they do, they can be easily caught at the exits).</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Drivers may use managed facility to temporarily bypass areas of congestion.</li> <li>– Easy for violators to exit lane before tolling or enforcement checkpoints.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ May discourage violators from entering facility to bypass congestion.</li> <li>– Cannot guarantee compliance.</li> </ul>
<b>2. Compliance is not a primary issue</b>	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
<b>VII. Cost</b>			
<b>1. First or capital or initial costs</b>	<b>No</b> <ul style="list-style-type: none"> <li>– High cost for material and installation.</li> <li>– Additional right of way required for placement of barriers.</li> </ul>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Low initial cost (same as with any regular lane).</li> <li>– If wide buffer is used, may need to purchase additional right of way.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ Cheaper than barrier; more expensive than buffer.</li> <li>– Wider buffers will require additional right of way purchase</li> </ul>
<b>2. Maintenance or replacement costs</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Requires very little maintenance; only necessary after serious accidents.</li> <li>– Protective barrels will need to be replaced fairly frequently.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Relatively frequent re-striping necessary.</li> <li>– Reflectors may need to be replaced frequently.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Posts need to be replaced on a weekly basis.</li> <li>– Requires re-striping of paint.</li> </ul>



	Concrete Barrier	Buffer	Post
<b>VIII. Safety</b>			
<b>1. Safety for managed lane users</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Provides protection from swerving vehicles from adjacent general-purpose lane.</li> <li>+ Provides protection from high-speed differentials with adjacent general-purpose lane.</li> <li>+ If access to facility is provided via t-ramps, no weaving is necessary.</li> <li>– If direct connections are not provided, drivers face the potential of striking the edge of the barrier when entering the facility.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– No protection from swerving/wayward vehicles</li> <li>– Drivers must weave across main lanes to access managed facility.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– No substantial protection from swerving/wayward vehicles.</li> <li>– Drivers must weave across main lanes to access managed facility.</li> </ul>
<b>2. Safety for users of non-managed lanes</b>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Provides protection from swerving vehicles from managed lanes.</li> <li>+ Provides protection from speed differentials with managed lane.</li> <li>+ If access to facility is provided via t-ramps, no weaving is necessary.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– No protection from swerving/wayward vehicles</li> <li>– Main lane motorists will have to deal with managed-lane users weaving across the main lanes.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– No substantial protection from swerving/wayward vehicles</li> <li>– Main lane motorists will have to deal with managed-lane users weaving across the main lanes.</li> </ul>
<b>IX. Aesthetics</b>			
	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Can be painted if desired</li> <li>+ Provide neat, straight lines (looks engineered).</li> </ul>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ Look identical to regular lane striping.</li> </ul>	<b>No</b> <ul style="list-style-type: none"> <li>– Posts are often considered very ugly, particularly if missing posts are not replaced promptly.</li> <li>– Struck posts may litter the road.</li> </ul>
<b>X. Constructability</b>			
	<b>No</b> <ul style="list-style-type: none"> <li>– Requires substantial construction effort to install.</li> </ul>	<b>Yes</b> <ul style="list-style-type: none"> <li>+ No additional construction effort required.</li> </ul>	<b>Maybe</b> <ul style="list-style-type: none"> <li>+ Easy to install; in simplest application, posts can be glued to pavement surface.</li> </ul>

## 2.4 Lane and Shoulder Width

Based upon generally accepted American Association of State Highway and Transportation Officials (AASHTO) standards, ideal lane width is taken to be 12 ft. Ideal shoulder width is more variable, but both the expert panel and the literature agreed that there is a range between 4 and 8 ft that should be avoided because a shoulder with a width in that range will appear to be a safe refuge while actually offering little protection for a stopped vehicle. As a compromise, 8 feet was taken to be the ideal shoulder width.

### Lane and Shoulder Widths are Less Than Ideal

The capacity of main lanes may decrease substantially if the available cross-section width is less than ideal. This has been dealt with in some areas by keeping trucks out of certain lanes and then decreasing the width of those lanes. For situations in which the type of delineation used does not physically separate the managed lane from general-purpose lanes (buffer and posts), having less than ideal lane widths can cause the level of service of the managed lane to decrease, especially if the main lanes are congested, because drivers will be wary to maintain a high speed differential between themselves and the adjacent lane. Furthermore, whatever speed differential does exist will tempt drivers to cheat and cut into the managed lane at undesignated areas; these drivers will be aided by the lack of a substantial buffer because of the restricted cross section.

A barrier will mitigate the negative effects of a speed differential, but the increased space requirements for barrier delineation may make the managed lane unworkable with restricted widths. A barrier itself physically occupies about 2 ft, according to FHWA's *Guide for HOT Lane Development*, and requires a buffer of at least 2 ft on either side (4). Furthermore, because barriers prevent vehicles from moving out of the managed lanes, much more width is necessary to allow drivers in the managed lane to bypass disabled vehicles and emergency response vehicles to reach incidents. The Caltrans design guide suggests a minimum of 21 ft between barriers, which would allow drivers to bypass a stalled bus (10). These considerations are moot for buffer and post, which do not restrict movement into and out of the managed lane.

Because posts and buffers can be implemented with far less cross sectional width than barriers, these delineation techniques are usually preferable in restricted-width conditions. Posts may make drivers feel like they have less room than they actually do, potentially diminishing the level of service beyond a level that is already diminished by restricted lane widths. Furthermore, posts require more space than do pavement markings: a single 8-in. stripe (13) may suffice without posts, but because the presence of posts makes drivers uncomfortable, the panel recommended at least 1 ft of buffer on either side of the posts for a 2-ft total; this buffer also helps to prevent accidental damaging of posts.

### Minimal or No Shoulder Available for Managed Lane

A shoulder is absolutely necessary for barrier-separated lanes. Even an ideal, 12-ft lane is far less than what is needed for passing accidents and for emergency vehicle access. The expert panel discussed a number of minimum and ideal total special purpose cross-sections; 18 ft was suggested as an absolute minimum, amounting to a 12-ft lane, a 4-ft shoulder on one side, and a 2-ft shoulder on the other. A range of 22 ft to 26 ft was considered ideal: 12-ft main lane, one 8-ft shoulder, and one 2-ft shoulder. Shoulder specifics were also considered: shoulders widths between 4 ft and 8 ft should be avoided, because such widths give drivers the impression of a full-sized, safe shoulder without actually providing much of a haven.

If at least 18 ft, preferably 22 ft, total cross section cannot be given to the managed lane, barrier delineation should not be considered.

## **2.5 Traffic Considerations**

### **Congested Traffic Conditions on Main Lanes**

For the expert panel discussion, congested traffic conditions were considered to be those with a HCM LOS of E, corresponding to  $V/C = 0.85$  at 70mph. This is considered an unstable condition; any perturbation can throw the system into a stop-and-go state. A special-purpose lane on a highly congested freeway is likely to experience a much higher level of service than are the main lanes (in fact, this differential is often the point of having a special-purpose lane in the first place). A speed differential is likely to affect the maximum level of service attainable on the special purpose lane if post or buffer is the delineation used because managed lane users may be wary of speeding past slower-moving main lane traffic that could dart out in front of them at any time; the expert panel believed that the maximum speed differential that most drivers are comfortable maintaining is about 15 mph.

Barriers have the unique property among delineation techniques that they are unaffected by speed differentials. Because errant drivers cannot simply cross the barrier at any time, users of the special purpose lane will feel much more comfortable with a higher speed differential. Barriers are, therefore, the delineation technique of choice for congested freeways.

### **Trucks Allowed on Special Purpose Lanes**

The expert panel strongly discouraged allowing trucks on a single lane special-use facility because trucks tend to clog lanes, especially on steep vertical inclines. Barrier separated facilities are especially susceptible to this problem because motorists will be unable to exit the managed lane to get around the slow trucks. Nevertheless, the panel still believed barriers to be the only acceptable delineation technique in the less-than-ideal situation of allowing trucks on single lane facilities; only barriers can provide the necessary physical separation between potentially fast-moving trucks in the managed lane and slower-moving traffic in the main lanes. Buffers and posts should not be used because drivers in the adjacent main lanes will inevitably find themselves being passed by fast trucks in the managed lanes. Post delineation suffers further when trucks are allowed on a facility with minimal shoulders because trucks with wide loads tend to mow down posts.

The panel also warned that overhead bridges might not provide sufficient vertical clearance on the edges of the road, where managed lanes tend to reside, to allow tall trucks to pass underneath. If trucks are to be allowed on a planned HOT or HOV lane, overhead clearance should first be checked to see if the idea is even feasible.

### **Buses on Special Purpose Lanes**

Many HOV and HOT lanes also serve as bus lanes, and the expert panelists have had no problems in their experiences with such duality. Though buses and trucks share many characteristics, both being slow, hulking vehicles, bus drivers, because of their employment as public-service figures, are thought to be more manageable and drive more safely and predictably. Truck drivers, answerable to many different companies and struggling to make deliveries on time, may weave between main lanes and special purpose lanes in erratic ways that seem to them to be advantageous. The expert panel therefore felt that buses could safely use special-purpose

lanes delineated with any technique. Posts face the relatively minor problem of being knocked down by buses; the expert panel recommended a buffer of 1 ft on either side of the post to mitigate this problem.

## **2.6 Centerline Geometry**

### **Less than Ideal Horizontal Curve Radius**

In the rare case that a horizontal curve on a freeway has a radius that is small enough to cause problems, the expert panel believed issues related to stopping sight distance to be the most important. Lanes separated by buffers and posts may not suffer from problems any different from those of the main lanes, but barrier-separated lanes need to have sufficient cross section to allow drivers to get out of the way of an incident that they are unable to see until the last moment. For barrier-separated facilities, the panel considered 18 ft to be the minimum advisable width and 22 ft to 26 ft to be ideal. If this amount of space is available, barrier is probably the preferred delineation technique; panicking drivers dodging an incident at the last moment, instead of potentially hitting a car in the adjacent main lane, will find themselves on the clear shoulder of the managed facility.

The HOV Systems Manual also points out that if buses are allowed to use a managed lane, the lanes must accommodate these larger vehicles and their unique turning characteristics (11).

### **Less than Ideal Vertical Curve Length**

If a crest vertical curve does not have an ideal length, stopping sight distance for any type of lane will be affected. Buffer- and post-delineated facilities should not suffer any more than normal traffic lanes, but barrier separation requires that an adequate amount of right of way exist within the facility to allow a user to swerve out of the way of an incident. The expert panel considered 18 ft to be the minimum space between barriers in a barrier-separated managed lane; 22 ft to 26 ft was considered ideal. Given that ideal width, the barrier would be the preferred delineation mechanism for situations with crest vertical curves of less than ideal length for the same safety reasons as previously mentioned for horizontal curves.

## **2.7 Freeway Main Lane Entry/Exit Considerations**

### **Frequent Main Lane Entrance/Exit Ramps**

Frequent entrance/exit ramps situations are taken to be situations in which the spacing between successive ramps is less than one mile.

Because barrier-delineated facilities are physically separated from activity on the main lanes, the frequency of entrance and exit ramps on the main lanes is irrelevant to these facilities. Furthermore, the entrances and exits for barrier-separated facilities are often placed off the freeway via t-ramps so that these facilities are often completely isolated from the rest of the highway.

Facilities using buffer delineation, and posts, to a lesser extent, may be affected by the frequency of main lane ramps. Drivers in the special-use lane that want to exit at one of the freeway exits that are not served by exits from the special-use lane may be tempted to cheat and illegally cross the buffer. A similar situation can potentially occur when drivers entering from the main lanes want to cross the buffer early. Some of these problems may also manifest in post-

separated facilities, especially if the spacing between posts is significant. Entrances and exits for the managed lane could possibly be matched to those of the main lanes, but frequent entrances and exits potentially diminish the level of service in the managed lane. On the other hand, if traffic volume on the managed lane is high, having infrequent access points to the managed lane requires that more vehicles cross into and out of the special-use lane at each weaving section. Fortunately, because pavement markings and posts are easy to change, more entry and exit points are simple to add in the future if specific areas are found to suffer from massive weaving problems.

## **2.8 Managed Lanes/Exit Considerations**

### **Entry/Exit Operations**

Weaving at managed-lane entrances poses a problem for buffers and posts. Because these access points are located on the freeway, interested drivers must work their way across all the lanes from the main lane entrance to the managed lane entrance. This maneuvering can affect service on the main lanes and can be risky in high-speed situations where misjudgments may prove hazardous. If entrances to barrier-delineated facilities lie off the freeway via grade-separated t-ramps, barrier-delineated facilities will not generally suffer from any entry or exit operational difficulties. Drivers entering the freeway via a t-ramp can potentially hit the edge of the barrier, but because these entrances are off the freeway where speeds are lower, the chances of this happening are low, and any incident will most likely be minor.

The problem of weaving also exists at the exits for managed lanes delineated by buffers or posts. Drivers exiting the managed lane must weave across several lanes of traffic to reach their desired freeway exit. T-ramp exits for barrier facilities pose no specific operational problems.

The expert panel discouraged use of *slip ramp* or simple weave-type entry facilities for barrier-separated facilities on the freeway. Such an entry arrangement introduces the possibility of drivers hitting the edge of the barrier head on at high speeds. Furthermore, users will find themselves battling the same weaving problems that plague buffer- and post-delineated facilities while entering and exiting. In addition, exiting users may be surprised by the abrupt change from the safe and controlled environment of a barrier-separated facility to one where they are no longer protected from vehicles in adjacent lanes.

Caltrans' *High-Occupancy Vehicle Guidelines for Planning, Design, and Operations* provides a suggestion for dealing with weaving problems on buffered facilities: if a wide buffer, with at least 12 ft to 16 ft in width can be provided, then portions of the buffer can be used for acceleration and deceleration lanes (10). Consequently, the merge from a speedy managed lane into a slow, congested general-purpose lane is very similar to the familiar task of exiting normal freeway lanes.

### **Entry/Exit Accessibility and Utilization**

Because access points for barrier-delineated facilities in the form of t-ramps are very expensive and because dropping the barrier creates a weaving situation that is not as safe as that of pylons and buffers, barrier-separated facilities generally have relatively infrequent entrances and exits. If access is provided by t-ramps with entrances and exits located off the freeway, drivers may have a difficult time finding those entrances and exits; they may even believe the managed lane to be a mysterious curiosity off-limits to them. Furthermore, barrier arrangements

are highly inflexible. If an additional entrance or exit were desired in the future, adding an appropriate ramp would be very costly. In contrast, because dropping buffer or post delineation is easier and less costly, facilities with these types of delineation tend to have more access points and can therefore target a larger pool of drivers. Between buffers and posts, buffers are easier and less expensive to manipulate; removing or adding posts, though not difficult, is not as inexpensive or easy as painting or removing a buffer marking.

Barrier separation is desirable if strict control over accessibility is desired. For example, a city may desire a managed lane to service primarily long distance travel between downtown and the suburbs; this can be accomplished by the strategic placement of entrances and exits. Such control is less available with posts, and almost completely nonexistent with buffers, because people can theoretically cross into the special-use lane wherever they desire.

## **2.9 Compliance Issues**

### **Strict Compliance Desired**

Barriers provide the most effective methods of enforcement. The simple prospect of being trapped in the barrier will dissuade many would-be managed-lane violators. The impenetrable barrier also stops any violators who would otherwise enter or exit the facility at unauthorized locations.

Posts emulate, but cannot quite match barriers in terms of compliance. At reasonably non-congested speeds, drivers zooming by will see the posts as a blurry, impassable wall. However, at lower speeds associated with more congested levels of service, frustrated drivers may try to cross between the posts; smaller spacing between posts will discourage these attempts.

Buffers are the worst delineation choice if strict compliance is required. Because there is no huge hurdle to crossing over the buffer, violators can potentially enter and exit the managed facility at will. Interestingly, early experience with buffer-separated HOT lanes suggests that these fears may be unfounded; Washington State, for example, has experienced very reasonable violation rates below 10 percent. In any case, a substantial buffer can discourage casual violators. If the facility is tolled, expensive toll-tag readers may need to be installed quite frequently to make avoiding the reader more difficult.

For any type of delineation, hefty fines, visible cameras, and palpable enforcement presence can help deter violators.

## **2.10 Costs**

Barriers have by far the highest upfront costs. The concrete itself is expensive, and installation requires heavy machinery and often the closure of several main lanes. If t-ramps are used for entry and exit, the capital costs increase even further. Posts, at \$40 apiece and placed one every 10 to 20 ft, have a nontrivial cost that is still relatively low compared to that of barriers. Pavement markings have by far the lowest upfront costs.

Roles switch when maintenance costs are considered. The barriers that are so costly to initially install will essentially perform at par forever with little maintenance. However, barrier systems do suffer from some minor, but necessary, ongoing costs. Barrels protecting protruding sections of barrier must be replaced fairly frequently and, when damaged, promptly. Furthermore, because barriers typically require more cross-sectional area within the managed lane, barrier-separated lanes have more asphalt that requires maintenance. Additionally, drainage

holes in the barriers may get clogged and need to be cleaned. Finally, barriers are occasionally damaged and require replacement or repair, which can be costly and inconvenient. However, most of these concerns are minor and are negligible compared to the resilience and efficiency of concrete barriers.

Upkeep costs for posts, on the other hand, are enormous. Posts are constantly knocked over by accident (or in some cases, for amusement), and panelists with post experience report that they replace about fifty per week on average. One bored driver, who realizes he can safely ride over posts without damaging his car, can destroy hundreds of posts at one time. Costs associated with replacing these posts can become astronomical.

Maintenance costs for buffers fare somewhat better than those for posts. Panelists reported that new forms of pavement marking can sometimes outlive the pavement itself. However, at areas of heavy crossing, pavement markings will need to be repainted every couple of years. Reflectors will also need to be checked for effectiveness; they can be knocked off or painted over. Maintenance of buffer paint is particularly important because the buffer is all that is separating two lanes of traffic, which often have very different speeds and vehicle compositions.

## **2.11 Safety**

Concrete barriers are generally accepted as the safest delineation method for managed lanes. Barrier delineation provides physical separation from the main lanes; drivers on the managed lanes do not have to worry about any speed differentials or violators from the main lanes swerving into the managed lanes. Furthermore, because entrances and exits to barrier-separated facilities are often placed off the freeway via t-ramps, users entering and exiting the facility do not have to deal with any tricky maneuvering involved with weaving. Additionally, the lower speeds involved with entering a managed facility via a t-ramp can decrease the risk of collision with the edge of the barrier, which may be only protected by barrels.

Barriers lose some of their advantage in safety when entrances and exits are accessible to the freeway main lanes. Cars interested in driving on the managed lane will have to weave across several lanes of traffic and then worry about striking the edge of the oncoming barrier at high freeway speeds. Cars exiting the facility will likewise have to weave across all intervening main lanes to reach their desired exit. The expert panel preferred the use of t-ramps to allow users to directly access the special-use facility instead of placing entrances and exits on the main lanes.

An additional safety concern of barriers is that when cross sectional width is limited, cars may not be able to pass stalled vehicles. This is of particular concern when stopping sight distance is limited and drivers cannot perceive a stopped vehicle until there is no longer time to safely stop. Because of this possibility, the expert panel strongly recommended using a cross section of no less than 18 ft.

The expert panel believed that neither post nor buffer styles of delineation is as safe as concrete barriers. Because there is no impassable separation between managed lanes and main lanes, drivers from either side may cross the boundary, on purpose or by accident, endangering those on the other side. Additionally, the entrances and exits to facilities with these types of delineation are generally freeway weaving sections; drivers entering or exiting the managed lane must perform potentially risky maneuvers to cross the main lanes. The weaving problem is more apparent at higher speeds; in congested conditions, the slower speeds may facilitate the process, although weaving drivers will need patience to find adjacent cars that will allow them to merge.

The relative safety characteristics of posts and buffers were basically a toss-up; each technique offered some safety advantages over the other. Because many drivers believe they will

damage their cars by driving over posts, fewer violators will be tempted to illegally cross into the managed lanes. Furthermore, because entrances and exits are more controlled than are those for buffer separation, there are fewer locations where weaving will be an issue. The experience of the panelists suggested that fears of broken posts being kicked up and damaging other cars are largely unfounded. However, because some drivers are reluctant to cross over posts, fearing damage to their cars, they may be more likely to crash into a suddenly stopped car ahead of them than they are to cross the post-delineated boundary into an empty lane. This is particularly a problem at high speeds, where the posts may blur together into what appears to be a solid wall.

In buffer-separated facilities, illegal weaving may pose a problem, especially if the speed differential is high. Additionally, accidents in the managed lane can affect the main lanes and vice versa because the facilities are not independent. However, in time of need, drivers have the ability to pass over the buffer.

## **2.12 Aesthetics**

Barriers were not seen to pose any huge aesthetic problems, although the panelists recognized that some people might take offense to the *concrete jungle* that they see as comprised in part by concrete barriers. Barriers can also often make drivers feel a claustrophobic *tunnel effect*. However, the panelists have witnessed many successful attempts to beautify barriers, including murals painted on the barriers and plants placed in specially designed barriers. Additionally, concrete barriers may represent, to some people, impressive engineering symbols.

Posts are uniformly regarded as unattractive; they frequently get knocked down, leaving unsightly gaps in the post succession. Posts that are knocked down tend to lie around, littering the freeways.

The expert panel agreed that buffers and pavement markings are the most aesthetically tasteful of the delineation techniques.

## **2.13 Constructability**

Concrete barriers are the most difficult of the delineation techniques to install. Their heft necessitates the use of huge equipment to lift the barriers and set them in place. This equipment often takes up several lanes of traffic, thereby decreasing the capacity for the rest of the freeway. Buffers and posts do not pose any special constructability issues.

## **2.14 Summary**

Although the previous discussion has presented detailed delineation selection considerations, the Expert Panelists clearly noted that within their collective experience, all three delineation families have been proven both safe and effective. That is, most delineation situations are unique and there is no single delineation method that is uniformly superior in all situations.



## Chapter 3. Comparison of Expert Panel and Literature-Based Recommendations

Because the recommendations of this expert panel, like those of any panel, are necessarily recommendations of a subset, albeit a presumably knowledgeable subset, of the population, they do not necessarily reflect the thoughts and experiences of all individuals with a history of working with managed lanes. Therefore, a comparison of the discussions of this panel with the findings of previous research is an important step for calibrating the results and putting them to use. This chapter summarizes the panel's input and the recommendations of existing literature with regards to each topic of consideration.

### 3.1 Lane and Shoulder Width

#### Lane and Shoulder Widths are Less Than Ideal

**A. Expert panel:** Barriers may be difficult if not impossible to use with constrained widths because they require the most right-of-way of the delineation methods for proper implementation. However, with reduced cross sections, posts and buffer methods may lead to a drop in capacity, as these methods lead to unprotected speed differentials.

**B. Literature:** The literature agrees with the expert panel: buffers and posts are generally the choice methods of delineation in situations of restricted width. The FHWA's *A Guide for HOT Lane Development* (14), while not specifically stating this preference, suggests that "one primary advantage to the (posts) is that they do not add to the right-of-way requirements." However, the *Guide* notes that "slip ramps require additional pavement area;" because slip ramps are often the access method of post- and buffer-delineated facilities, the placement of these ramps must be carefully coordinated with right-of-way data to insure successful implementation for these types of managed lanes.

The *Guide* suggests that 18 ft—a 12-ft lane, 4-ft shoulder, and 2-ft barrier—is the minimum amount of room needed for a barrier-delineated facility, which is a more liberal estimate than the panel's recommendation, which includes an additional 2-ft shoulder. FHWA's *HOV Lane Safety Considerations Handbook* agrees with the 20-ft estimate of the panel and further warns that any width greater than 22 ft may encourage drivers to attempt passing maneuvers, which may be undesirable on a managed facility (12).

The *HOV Lane Safety Considerations Handbook* also agrees with the panel that concrete barriers require a lot of right-of-way. With restricted right-of-way, there may not be enough room to place a shoulder on the main-lane side of the barrier, and this "close proximity of the median barrier to general-purpose traffic can lead to multiple-vehicle crashes if a vehicle strikes the wall and is deflected back in the traffic lanes." In addition, if a barrier installation negates the possibility of having a left shoulder on the main lanes, disabled vehicles on the general-purpose lanes will have to travel across all other lanes to get to the right shoulder.

As the expert panel pointed out, "the inability of a vehicle to exit a barrier-separated facility in the event of an emergency can also disrupt operations and generate secondary incidents, particularly if there is limited space within the facility." The *Handbook* continues: "Because drivers in the HOV lane do not generally expect to encounter stopped traffic, slowing down and maneuvering around a disabled vehicle can be an unexpected and dangerous event."

Therefore, whenever barriers are used to delineate managed lanes, a significant amount of room is necessary to allow drivers to deal with unexpected events. When posts or buffers are used, drivers in the managed lane can swerve into the main lanes to avoid these unexpected events.

The *HOV Lane Safety Considerations Handbook* suggests that an extra-wide buffer of at least 10 ft can address some of the safety concerns of buffer-delineation; obviously, if the right-of-way is restricted, these wider buffers will not be feasible. If only a narrow buffer is provided, drivers will feel uncomfortable driving with a substantial speed differential between them and the adjacent lane.

The *Handbook* also relates how HOV operators in California chose post-delineation along SR 91 because right-of-way restrictions along the corridor ruled out barriers. Furthermore, crash data indicate that the incident rate along SR 91 is comparable to other facilities.

### **Minimal or No Shoulder Available for Managed Lane**

**A: Expert panel:** Adequate shoulders are necessary for a barrier-separated managed lane; without a shoulder, disabled vehicles on the managed lane will have no refuge and will therefore be forced to block traffic. Shoulders are also preferable for buffer- and post-delineated facilities but aren't absolutely necessary because traffic on the managed lane can pass disabled vehicles by crossing the boundary.

**B: Literature:** The literature agrees with the panel: shoulders in the managed facility are important. FHWA's *A Guide for HOT Lane Development* states that "a minimum four-foot shoulder is required between the HOT lane and the barrier," and a 10-ft shoulder is preferable.

FHWA's *HOV Lane Safety Considerations Handbook* agrees that shoulders are important on managed lanes but further emphasizes the importance of shoulders for all types of delineation, not just barrier. Shoulders are necessary for allowing disabled vehicles to pull over without interfering with other traffic. However, "designated breakdown areas within the facility where wide continuous shoulders are not feasible" can help offset the impact of narrow or nonexistent managed-lane shoulders on barrier-separated facilities.

Part of a 2003 TTI study of managed lanes was a survey of practitioners. Most of the surveyed individuals felt that an adequate shoulder is critical for the success of a managed facility with any type of delineation. Buffer-delineated facilities face the potential problem that drivers may think the managed lane is the shoulder if none is actually provided; if their car breaks down, they may park on the managed lane and block traffic. The survey also revealed that most HOV practitioners believe barrier-separated facilities should have shoulders too; "crashes within barriers of an HOV lane can make incident management difficult, particularly if the facility lacks shoulders."

## **3.2 Traffic Considerations**

### **Congested Traffic Conditions on Main Lanes**

**A: Expert panel:** With posts or buffers, congestion on the main lanes can cause a speed differential between the managed and main lanes that may increase incident risk and driver discomfort. The physical protection provided by concrete barriers negates the negative effects of speed differentials; therefore, concrete barriers are preferable when the main lanes have high levels of congestion.

**B: Literature:** The literature agrees that concrete barriers are the best form of delineation to negate the effects of a speed differential caused by congested traffic conditions. According to

FHWA's *A Guide for HOT Lane Development*, "since there are often high speed differentials between the general-purpose lanes and HOT lanes, physical barriers...help maintain safety by preventing potential violators from crossing the buffer into the HOT lanes and disrupting the traffic flows." Furthermore, barriers "are more effective at...maintaining premium traffic service" because they "prevent unauthorized vehicles from entering the managed lanes"; at more congested conditions, more drivers may be tempted to cheat and unlawfully enter the managed lane if they are only prevented by a buffer or post.

FHWA's *HOV Lane Safety Considerations Handbook* agrees; concrete barriers protect drivers in both the managed lanes and the general-purpose lanes from any speed differential that may exist between the two lane types.

Another study compared different types of buffer-separated managed facilities. The study found that buffer widths of less than 2 ft led to an incident rate that was higher than what would have been expected if a general-purpose lane had been added instead. The study reasoned that the increased incident rate was caused by a speed differential between the managed lane and the general-purpose lane and that a strong form of delineation can weaken the effects of this differential (8).

### **Trucks Allowed on Special Purpose Lanes**

**A. Expert panel:** The panel discouraged allowing trucks on any single-lane managed facility: buffers and posts do not protect general-purpose lanes from the trucks if a speed differential exists (as it likely will), and barriers require significant additional width to allow disabled or slow-moving trucks to be passed safely.

**B. Literature:** The literature reflects mixed feelings about allowing trucks onto managed facilities. As FHWA's *HOV Lane Safety Considerations Handbook* points out, there has been no thorough analysis of trucks on HOV lanes performed. Virginia is the only state currently allowing heavy trucks on its HOV lanes, and even it restricts trucks to HOV lanes on Interstate roads with more than two lanes in each direction. Because other areas are curious about the possibility of allowing trucks on HOV lanes to reduce conflicts in the main lanes, much more research is likely in the near future.

However, the authors of the *Handbook* itself seem to disapprove of the idea of allowing trucks on managed lanes. "The unique characteristics of heavy trucks (including their weight, dimensions, acceleration and deceleration characteristics, and turning radii) could require design, maintenance, and operational considerations that diverge significantly from those of existing HOV facilities. The potential for increased crash severity as a result of the mixing of passenger vehicles and heavy trucks on HOV lanes poses additional concerns. Other potential safety-related issues include degradation of facility performance and responder access, sight-distance deficiencies, enforcement difficulties, and conflicts with supporting facilities such as direct ramps."

There has been no thorough research into the connection between truck use on managed facilities and type of delineation used.

### **Buses on Special Purpose Lanes**

**A. Expert panel:** All delineation methods have been successfully used with buses in the managed lanes. However, when buses are allowed in the lanes, they, like trucks, may reduce the overall speed of the managed lanes. Additionally, with buffer separation, buses may encourage

personal vehicles to weave excessively in and out of the managed lanes to complete passing maneuvers.

**B. Literature:** The literature overwhelmingly supports the assertion that buses perform well on managed facilities with all types of delineation. After all, as FHWA's *HOV Lane Safety Considerations Handbook* mentions, the first HOV lane was a busway, and most managed lanes since have been designed to accommodate buses. The *Handbook* also supports the idea that bus drivers can be relied on to act professionally when it notes that "contraflow facilities separated by plastic pylons are sometimes restricted to professionally trained drivers such as bus drivers." The *Handbook* authors also prefer to restrict managed lanes with excessively restricted right-of-way to buses—again because of the drivers' supposed professionalism. This recurring idea of professionalism in bus drivers suggests that these drivers can handle a huge bus as well as a normal driver can handle a small car. Differences in the professionalism of their drivers may be the reason that buses are considered tenable on managed facilities and similarly sized trucks are not.

### 3.3 Centerline Geometry

#### Less than Ideal Horizontal Curve Radius

**A. Expert panel:** Posts and buffers may cause problems on tight curves if there is a speed differential between the managed lanes and the general-purpose lanes. Barriers may restrict drivers from being able to swerve around objects that appear faster than expected because of the reduced sight distance on tight curves.

**B. Literature:** There has been very little research into the problems associated with tight curves and different delineation techniques on managed lanes. FHWA's *A Guide for HOT Lane Development* notes that "when determining the locations of slip ramps, local topography, lines of sight, and operating characteristics of adjacent lanes need to be taken into consideration."

The authors of FHWA's *HOV Lane Safety Considerations Handbook* argue that "median or lateral barriers and glare screens may obstruct sight distances around curves and at other locations." Furthermore, "these treatments may have to be adjusted or removed in specific areas for safety purposes." It seems reasonable to assume that because of this consideration, posts and buffers may be preferable to concrete barriers in areas of many tight curves.

A 2003 TTI survey found that some HOV practitioners believed that "barrier-separation may create problems with sight distance at access points and horizontal curves, particularly when the HOV lane is operating during non-daylight hours. This situation requires ample signing and illumination to increase the level of safety."

#### Less than Ideal Vertical Curve Length

**A. Expert panel:** If a short vertical curve restricts sight distances, drivers may not have time to stop to avoid a collision and will instead have to swerve out of the way. With posts and buffers, drivers can swerve out of the way of upcoming objects, but with concrete barriers there may not be enough room for a safe maneuver.

**B. Literature:** Very little has been said in the literature about problems that may exist with combinations of restricted vertical curve length and different delineation techniques. FHWA's *A Guide for HOT Lane Development* simply notes that "when determining the locations of slip ramps, local topography, lines of sight, and operating characteristics of adjacent lanes need to be taken into consideration."

### 3.4 Main Lane Entry/Exit Considerations

#### Frequent Main Lane Entrance/Exit Ramps

**A. Expert panel:** If barrier separation is used, access via fly-over lanes will insulate the managed facility from any conflicts with main lane entrance and exit ramps. With posts and buffers, frequent access points to and from the managed lanes will require more frequent weaving movements throughout the length of the facility. With infrequent access, there will be higher volumes at each access location that is provided.

**B. Literature:** The literature agrees with the expert panel; the frequency of main lane entrances and exits can have a negative influence on the operations of the managed lane if weaving maneuvers are required for access to the managed lane, but it is unlikely to have any effect at all if direct-connection techniques are used. Because direct connections are most frequently used with barrier-delineation and weaving sections, with posts and buffers, it is a small jump to interpret this to mean that barriers are the preferred form of delineation on freeway segments with many access points.

FHWA's *A Guide for HOT Lane Development* acknowledges the connection between access points for main lanes and managed lanes by pointing out the need for coordination between them to provide enough space for drivers to safely weave across lanes. Furthermore, because the weaving sections used primarily with buffers and posts (but sometimes also with barriers) tend to concentrate entrances and exits in discrete locations, "there is a potential for bottlenecks to form near access points." In situations such as these, the *Guide* recommends installing grade-separated access like the direct-connection fly-overs most often used with barriers.

FHWA's *HOV Lane Safety Considerations Handbook* also agrees: "Limited-access HOV facilities with numerous intermediate ingress and egress sites may be especially vulnerable to (ingress-egress) safety-problems." Because pavement markings can technically be crossed at any point, buffer separation poses the most safety problems associated with high numbers of main-lane access points; posts and barriers more effectively limit weaving maneuvers to locations where they can be more safely executed.

### 3.5 Managed Lanes Entry/Exit Considerations

#### Entry/Exit Operations

**A. Expert panel:** Barrier facilities accessed by direct connections face no operational disadvantages; those accessed with weaving sections force drivers to face both the problems associated with weaving and also the possibility of hitting the edge of the barrier head on. Posts and buffers usually require the use of weaving sections, which can cause headaches for drivers on both the managed lanes and the main lanes; nevertheless, when direct connections are not feasible, the expert panel strongly preferred posts and buffers to barriers.

**B. Literature:** The literature agrees that the weaving sections used mostly with posts and buffers introduce operational problems that are not present with the direct-connectors that barriers frequently utilize. After stressing the issues associated with weaving maneuvers, FHWA's *A Guide for HOT Lane Development* notes that "grade-separated access for HOT lanes greatly reduces weaving and merging movements for vehicles entering or exiting a facility."

Likewise, FHWA's *HOV Lane Safety Considerations Handbook* notes that "flyover ramps and T-ramps are preferred for barrier separated HOV lanes" because they "eliminate the

need for vehicles to weave across multiple general-purpose lanes while rapidly accelerating or decelerating to access the HOV lane or exit the freeway” and allow “for greater HOV-lane volumes and fewer disruptions of general-purpose traffic.” In other words, if fly-over ramps can be installed, barrier is the type of delineation that is least likely to have a negative impact on managed-lane operations.

### **Entry/Exit Accessibility and Utilization**

**A. Expert panel:** Barrier-separated facilities necessarily have fewer access points, and those access points are difficult to change. Access points for buffer- and post-separated facilities are typically more frequent and flexible, and these facilities may be better utilized. If strict control over accessibility is desired, barrier separation is the preferred delineation method.

**B. Literature:** FHWA’s *A Guide for HOT Lane Development* agrees that barrier-separation allows for the best manipulation of access. However, little has been written about the overall level of utilization associated with each delineation technique.

## **3.6 Compliance Issues**

### **Strict Compliance Desired**

**A. Expert panel:** Barriers are the best method for ensuring enforcement and compliance. Posts exhibit some of the same enforceability characteristics, but they still lag behind barriers. Buffers are least likely to dissuade managed lane violators.

**B. Literature:** Barrier-separation is rather universally regarded as the best technique for reducing managed-lane violation rates. FHWA’s *A Guide for HOT Lane Development* asserts that “barriers...are more effective (than posts) at reducing violations” and are “preferable from enforcement...perspectives as they prevent unauthorized vehicles from entering the managed lanes.”

The *Guide* also provides guidelines for maximizing the enforceability of post-delineated facilities: “20-foot spacing between pylons is recommended,” and “it is also recommended that a minimum 18-inch striped buffer zone be provided on each side of the pylon.” The implication is that with sufficient resources (ability to buy many posts) and right-of-way (ability to provide a wide buffer), post and buffer delineation techniques may be able to approach the high compliance rates afforded by barriers. FHWA’s *HOV Lane Safety Considerations Handbook* agrees: “(posts) represent a strong visual and psychological barrier to buffer violations.” The *Handbook* also reports on an experiment in Dallas where posts installed on a portion of roadway “significantly reduced collisions involving unexpected maneuvers into and out of the HOV lane in the three years since their installation.”

## **3.7 Costs**

**A. Expert panel:** Barriers have the highest upfront costs, but their maintenance costs are negligible. Buffers are by far the least expensive form of delineation; paint will need to be maintained, but overall costs are low. The upfront costs of posts are low compared to barrier but high compared to buffers; posts’ maintenance costs are by far the highest.

**B. Literature:** There is no disagreement in the literature with the panel’s assessment of cost. FHWA’s *A Guide for HOT Lane Development* notes that “the cost of regular (daily) maintenance (for posts) must be weighted against those of other separation methods” because with a cost of \$60 each and replacement rate of about 10 percent every 60 to 90 days, posts are

expensive to maintain. In addition to being struck, pylons face other hardships: they “tend to turn black in color from the tires of vehicles that strike them” and thus “require considerable maintenance to remove debris and provide for their operability.”

Concrete barriers are very expensive to install, not just because of the cost of concrete and construction but also because of their considerable right-of-way requirements. However, the *Guide* notes that their “maintenance costs are low in comparison.” If the managed facility is not expected to face any changes for a long time, barriers may be more cost-effective than posts.

FHWA’s *HOV Lane Safety Considerations Handbook* concurs with the expert panel on another point: direct-access connections, usually associated with barrier-delineation, are very expensive, because of both their construction costs and right of way requirements.

### 3.8 Safety

**A. Expert panel:** Each type of delineation introduces various safety concerns. Barriers are considered the safest because they negate any problems related to speed differentials, and when direct connect ramps are used for access, barriers face no weaving challenges. The expert panel warned against providing freeway access to barrier-facilities; the potential for a driver to strike the edge of the barrier may be high. Weaving, both legal and illegal, can be a problem for buffers and posts; buffers may be violated by illegal weaving more than posts.

**B. Literature:** FHWA’s *A Guide for HOT Lane Development* agrees that barriers negate problems associated with speed differentials between general-purpose lanes and managed lanes—and these problems can otherwise prove hazardous. A TTI study released in 2003 studied crash data for HOV facilities in Texas and determined that most incidents occurring between managed lanes and general-purpose lanes are probably caused by speed differentials and that barrier-separated lanes did not experience these same incidents (7).

Barriers also “(prevent) potential violators from crossing the buffer into HOT lanes and disrupting traffic flows.” Furthermore, barriers “provide enhanced safety and are essential if reversible flow operations are being contemplated.” However, continuous barriers are not perfect; they may “increase response time for emergency vehicles and may hinder emergency response operations in the HOT lane.” Additionally, as FHWA’s *HOV Lane Safety Considerations Handbook* notes, barrier-separated facilities without sufficient right of way may pose a problem for drivers needing to slow down and maneuver around a disabled vehicle.

Interestingly, both *A Guide for HOT Lane Development* and *HOV Lane Safety Considerations Handbook*, contrary to the recommendation of the panel, suggest that providing at-grade access to barrier-separated facilities may be acceptable. The *Guide* provides diagrams to illustrate the implementation of barrier slip ramps without mentioning any particular safety problems with the arrangement. The *Handbook* notes that “at-grade access treatments may be considered when cost or right-of-way limitations preclude the use of direct-access designs.”

However, no source recommends the use of at-grade access when grade-separated, direct connections are feasible. According to the *Guide*, “grade-separated access for HOT lanes greatly reduces weaving and merging movements for vehicles entering or exiting a facility” and provides “acceleration and deceleration areas, which allow high-speed merges and diverges.” Furthermore, the *Handbook* notes that “the limited-access operation of barrier-separated HOV facilities concentrates weaving in the general lanes to particular locations upstream of HOV access terminals and downstream of HOV egress terminals” and that “weaving across congested general-purpose lanes to and from these access points is a relatively complicated maneuver that

degrades safety by exacerbating vehicle conflicts.” These safety concerns are obviously not relevant for direct-connections to barrier-separated facilities.

The literature agrees with the panel’s assessment of the safety of posts and buffers. Neither form of delineation can mitigate the dangers associated with speed differentials; according the *HOV Lane Safety Considerations Handbook*, speed differentials especially play a role at entry and exit points, where vehicles must slow down or speed up to match the speed of the traffic into which they are merging. The *Handbook* also points out that post- and buffer-delineated facilities require weaving sections that may pose a challenge for both drivers trying to access the managed lanes and other drivers on the main lanes. Additionally, unlike the panel, *A Guide for HOT Lane Development* says that pylons dislodged from the pavement may carry pieces of asphalt with them that may pose a hazard to traffic on the road. However, the *Guide* praises posts because they “allow emergency and maintenance vehicles to drive over them to take advantage of the higher travel speeds in the HOT lane.”

### 3.9 Aesthetics

**A. Expert panel:** Buffers are probably the best-looking delineation method because they match the décor of the rest of the highway. Posts are generally considered the least aesthetically pleasing, especially if dislodged posts aren’t replaced promptly. Barriers may seem menacing to some drivers, but they can be easily decorated.

**B. Literature:** Aesthetics considerations of managed-lane delineation techniques have not yet been studied in detail.

### 3.10 Constructability

**A. Expert Panel:** The construction of concrete barriers introduces many challenges, including possibly the closure of several main lanes to position appropriate equipment for lifting barriers into place. Buffers and posts are no more difficult to install than the delineation for normal highway lanes.

**B. Literature:** Constructability considerations of managed-lane delineation techniques have not yet been studied in detail. However, FHWA’s *A Guide for HOT Lane Development* does note that retractable pylons, a special subset of post-delineation, “require minor excavation at each post and the installation of electrical wiring beneath the roadway.” Special equipment is probably needed for this excavation, and, as for barriers, other highway lanes may have to be temporarily closed to position this equipment appropriately.

### 3.11 Summary

This chapter has presented a series of summaries of Expert Panel recommendations and statements regarding these recommendations provided in current literature. Generally, primary concepts that evolved through the Expert Panel discussions tend to closely parallel recommendations contained in current guidelines. Expert Panel recommendations tend to be well supported by the literature.



## Chapter 4. Summary and Recommendations

Managed lanes are growing ever more popular around the nation as a way to meet regional mobility needs, and transportation agencies are faced with a wide array of questions when considering their implementation. One decision that must be made before installation can begin is the type of delineation device used to separate the managed lane(s) from the general-purpose lanes. Three basic categories of delineation exist for this purpose: concrete barriers, pylon posts, and painted buffers. This research project assembled an expert panel to gather a collective knowledge of factors involved in the choice of delineation most appropriate to given scenarios. The summary of this panel's discussions, included in this paper, will serve as a useful guideline for engineers looking to choose the best type of delineation for future, successful managed lane projects.

The expert panel discussions led to several particular observations and recommendations:

- Generalizations about choosing the best form of delineation are very difficult to make because each distinct situation presents a vast, tangled web of different emphases, limitations, and demands. The Panel emphasized that different delineation devices exhibit both advantages and disadvantages under different scenarios; the magnitude of pluses and minuses can vary enormously from situation to situation. Managed facilities exist that demonstrate very successful applications of all types of delineation across a variety of scenarios.
- In cases of restricted right-of-way, buffers and posts are preferable to barriers. Concrete barriers should not be considered for single-lane facilities unless a barrier-to-barrier clear width of at least 18 ft can be provided.
- The expert panel strongly discouraged the use of concrete barriers without grade-separated, fly-over connections; weaving sections introduce the possibility of drivers striking the end of the barrier at high speeds.
- Concrete barriers provide the best means of controlling access and are therefore the best means of guaranteeing toll collection from all users.
- Buffer-type delineators are the least costly in terms of both initial and maintenance costs.
- Post type delineators can significantly reduce illegal crossing of the delineation zone, compared to buffer only installations, but represent large continuous maintenance costs.
- The Panel generally found posts to be the least favorable type of delineation. However, they agreed that posts could be used successfully to ease drivers into the idea of having a separated, managed facility that can only be entered at specific locations. Once the managed lane is established, the posts could be removed to leave just the buffer.

## 4.1 Recommendations for Future Research

- Very few tolled managed lanes utilize buffer delineation, so estimating violation rates that may be expected on buffer-separated, tolled lanes is difficult. A reasonable expectation is that drivers stuck in congested main-lane traffic will be tempted by the free-flow speeds maintained in the toll lanes and the ease of crossing a painted buffer to illegally access the toll facility. Clearly, buffers are more susceptible to these violations than are concrete barriers, but comparing violations rates of buffers and posts is more difficult. Because painted buffers are inexpensive, they may compare favorably overall to posts even if they suffer from a slightly higher violation rate. This comparison is impossible, however, without more data on violation rates for buffer-separated toll lanes.
- Little documentation exists on the effects of allowing heavy trucks on managed lanes. As the panel pointed out, heavy trucks may potentially disrupt traffic in the managed facility, especially on inclines. They also present a possible safety issue to cars in the adjacent lane if buffer- or post-type delineation is used. However, buses, which would seem to suffer from many of the same issues, perform perfectly acceptable on existing facilities; future data may shed some light on whether trucks actually present problems that buses do not.
- Both the expert panel and literature agree that posts can deter crossing-violations that may be more prevalent on buffer-separated facilities. This decrease in violations may be a result of drivers believing the posts are impassable and will damage their cars. However, is this a lasting deterrent, or will drivers treat posts like buffers when they discover the posts do not cause any damage? Future studies that analyze the violation rates of post-delineated facilities over long periods of time would help answer this question that may be critical for choosing between posts and buffer.

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