Appendix B. Limited Access Dual HOV White Paper

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ISSUES AND FACTORS INFLUENCING THE CHOICE BETWEEN CONTINUOUS- AND LIMITED-ACCESS MANAGED LANE FACILITIES

June 28, 2017

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EXECUTIVE SUMMARY

Recommendations incorporated in the Spine Corridor Master Plan include provision of additional "managed lanes" in three segments of the corridor. The term "managed lane" can refer to any lane that has restrictions or constraints on use; most commonly in the form of high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes. HOV lanes restrict use of the lanes to vehicles with a minimum number of occupants, currently two or more in the MAG region. HOT lanes allow single-occupancy vehicles (SOVs) to operate in the HOV lanes or a dedicated, separate facility for a price. When pricing is used in this manner to "manage" entry into the HOV lanes, the SOV operator gains the advantages of an HOV lane by paying a price that usually is adjusted in accordance with the time of day and volume of traffic using the facility.

Introduction of multiple managed lanes in the corridor may require modifications to the current configuration of the existing HOV lanes, which currently provide contiguous, continuous-access, concurrent-flow operation with the general-purpose (GP) freeway lanes. Limitations on access would continue to be asserted through restrictions on HOV lane eligibility – carpools, vanpools, motorcycles, buses, electric/hybrid vehicles – and the charging of a fee or toll to use the HOT lane, if HOT lanes are introduced in the corridor. However, with multiple managed lanes being introduced in the corridor, the future design of such facilities should consider the potential need to include a barrier to separate the managed lanes from the GP freeway lanes. In this case, the current operational characteristic of the HOV lanes – continuous ingress/egress – would be eliminated. Access to the managed lanes facility would be limited to specific locations. This operational scenario essentially creates express lanes for longer commute trips, as points of access (ingress and egress) generally are limited, allowing higher speed of travel and fewer potential conflicts.

Several issues have come to light regarding this potential barrier-separated, limited-access managed lane condition. These issues have been summarized in the following paragraphs.

ENFORCEMENT

Enforcement of managed lanes facilities is a challenging problem, and enforcement is more challenging with respect to painted stripe- and buffer-separated facilities. Active enforcement can be disruptive of the traffic stream in the GP freeway lanes, whereas enforcement within a managed lanes facility can be carried out, if necessary, more safely with provision of an inside, median shoulder sufficiently wide to accommodate stopped vehicles and associated pedestrian movements. The recommended strategies for the I-10/I-17 corridor do include provisions for such shoulders to facilitate enforcement of the managed lanes. In the case of HOT facilities,modern technology, i.e., electronic toll collection (ETC), that supports billing of HOT lane use through transponders and license plate scanning, is an effective and safe form of enforcement and most cost-effective, as the need to have an on-call enforcement official or patrolling official is significantly reduced. ETC is not associated with HOV use; therefore, active enforcement by police officials is required.

PUBLIC OPPOSITION TO MANAGED LANES

HOV facilities are an integral part of the transportation tool box to improve mobility and accessibility, especially in urban areas. According to the Federal Highway Administration (FHWA), HOV facilities "…serve to increase the total number of people moved through a congested corridor by offering two kinds of travel incentives: a substantial savings in travel time, along with a reliable and predictable travel time." The general consensus of the FHWA and many transportation specialists is that managed lanes free up capacity in the GP freeway lanes, and expectations are that this new capacity will allow greater mobility for the community/region overall. By shifting vehicles into the managed lanes congestion in the GP freeway lanes is reduced, which, in turn, results in higher overall average speed, reducing vehicle emissions through the corridor, increasing person throughput, and contributing to regional air quality goals. HOT lanes would allow motorists to opt for an alternative travel experience, per se, at a given price that generally varies throughout the day according to travel demand in the corridor where the facility is located.

Managed lanes generally are not viewed as degrading the overall mobility and safety performance of a freeway system. On the other hand, these facilities permit transportation officials to better manage roadway capacity to create the most efficient travel system possible throughout the day. There are those who present the case that expeditious travel in the managed lanes is critical to motivating use of the lanes. However, should congestion of the GP freeway lanes be relieved, there would be less incentive to use the lanes, let alone pay a fee in the case of HOT lanes. Therefore, ironically, the effectiveness of managed lanes is to a large degree dependent on continuing congestion in the GP freeway lanes. Latent demand has been shown to quickly absorb new freeway capacity. This means that, while person throughput has been increased by multiple persons in a greater number of vehicles in the managed lanes and speed in the managed lanes is higher, general corridor congestion is not necessarily relieved, as drivers using alternative routes, e.g., arterial streets, take advantage of the new capacity.

This dilemma of demand versus supply is precisely the impetus associated with developing and operating managed lanes. Operational adjustments must be made throughout the day to manage access to the managed lanes in such a manner (i.e., by time of day, price, or overall conditions in the corridor) as to optimize vehicle and person throughput while minimizing congestion in the GP freeway lanes. In the case of HOT lanes, the FHWA provides the following guidance respecting the operating strategy associated with managed lanes:

> *The toll should be varied in accordance with travel conditions and should be set at a high enough level that the performance of the HOV lane is not degraded. This optimizes the vehicle throughput of the HOT lane and reduces congestion in the general-purpose lanes by drawing off some of the SOV traffic that would otherwise be forced to use those lanes. So HOVs are no worse off, and vehicles that do not meet the vehicle occupancy requirement, whether they use the HOT lane or the general-purpose lanes, are better off.*[1]

Currently, managed lanes in Arizona are confined to HOV use only, and the option for HOT use of managed lanes facilities has not been introduced, in part due to the uncertainty regarding public opposition to the concept of tolling in general.

SAFETY PERFORMANCE

Specific, quantifiable information regarding the safety experience at access points has not been a focus of the many studies conducted to date. Available studies generally support the notion that limited-access, barrier-separated managed lanes facilities are safer than continuous, concurrent-flow facilities. The safety performance of such facilities primarily is associated with the design of access points and lane configurations. Available studies point to wider facility envelopes, including adequate inside shoulder widths, as a means to reduce crashes and the severity of crashes. Other factors for consideration to mitigate potential hazardous conditions are:

- Direct entry and exit to at-grade slip ramps or Direct HOV (DHOV) ramps from grade-separated arterial roadway via the inside GP freeway lanes, which minimizes immediate weaving and merging;
- Locating ingress and egress points away from freeway on- and off-ramps, which allows time to weave and merge;

1 Chapter V, Strategies to Reduce Congestion and Improve Air Quality in Federal-Aid Highway Program Guidance on High-Occupancy Vehicle (HOV) Lanes, September 2016, at https://ops.fhwa.dot.gov/freewaymgmt/hovguidance/chapter5.htm.

- Provision of adequate instructional/directional signage that informs motorists of advancing conditions; and
- Sufficient lighting to assure changing facility characteristics are easily seen.

FHWA Freeway Management guidance states "the safest HOV lanes are those that are physically separated from the adjacent lanes with a concrete barrier," and separation also creates greater safety for traffic in the GP freeway lanes. The recommendation to have managed lanes begin and terminate at DHOV on/off ramps would minimize the potential hazardous conditions associated with higher speed managed lane traffic merging with slower speed traffic in the GP freeway lanes. Overall, although safety is a real and valid concern, it cannot be the prime determinant for selecting a given highway treatment. The FHWA summarizes this issue in the following manner:

> *Managed lanes can provide safety and operational performance benefits over general-purpose facilities, but the managed lane strategy must be appropriate for the intended user group. Specific benefits in crash reduction seen at one facility do not necessarily translate to another facility, so the selected strategy must account for the conditions unique to a particular facility.*

To that end, the Minnesota Department of Transportation (MnDOT) completed a 2014 study titled "Evaluation of the Effect of MnPASS Lane Design on Mobility and Safety", which investigated and contrasted the closed access conditions on I-384 and the open access conditions on I-35W. The study resulted in the conclusion that both strategies can be effective, depending on the characteristics of the facility. According to a technical summary document of the study "*The research suggests that for most roads, an effective approach is to start with open access but periodically evaluate and limit access in specific areas as appropriate based on traffic density in the HOT lane and the speed differential between HOT and general traffic lanes.*" The study also provided design tools for use in future managed lane construction.

Effect on the Use of HOV lanes

The usual and customary use of the HOV lanes by carpools/vanpools, buses, motorcycles, and electric/hybrid vehicles, as permitted by HOV policies, would not be hampered. HOV lane-eligible users would be allowed access throughout the day. Facility level of service (LOS) would be determined in accordance with real-time observations of traffic and policies established for the facility. Generally, congestion within the freeway corridor during peak travel periods means there would be increased use of the managed lanes facility; therefore, if HOT lanes were introduced, peak periods would have the highest tolls as a discouragement for SOV operators, if congestion forms within the managed lanes facility.

Access to Established Traffic Interchanges Within the Spine Corridor

The inherent operational philosophy associated with development and implementation of managed lanes is to expedite commuter travel over longer distances. Because a good portion of urban freeway usage has become associated with localized movements of a few miles (even one mile or less), separating commuters brings relief to the GP freeway lanes of the burden of what essentially can be considered to be through-traffic movements. Although FHWA notes that access spacing of two to three miles is common for limited-access facilities, ADOT does recognize that barriers limiting entrance and, particularly, exit from a managed lanes facility can be a discouraging aspect for commuters, when exits are not convenient to their desired destination.

Design and location of access points (ingress and egress) not only affects user convenience but, also, safety and operational performance of the facility. Enforcement capabilities also can be affected, as well as facility design, which must support adequate transition zone length and safe positioning of ingress and egress points relative to on/off ramps of the freeway. In the case of the I-10/I-17 Corridor, freeway/arterial interchanges generally are spaced at one-mile intervals. This physical design of the freeway may require (1) DHOV connecting ramps at interchanges or (2) unique designs of at-grade slip ramps for ingress to and egress from the managed lanes in the center of the freeway. Option 1 would only be feasible at dedicated DHOV interchanges, allowing access to the center of the freeway, as is the case at Maryland Avenue on SR 101L in Glendale. Option 2 would require entrance to at-grade ingress slip ramps to be sufficiently far from a freeway on-ramp to assure adequate time for motorists to weave safely to the center lane for access to the slip ramp. The same would be true for motorists exiting the median managed lanes; sufficient distance must be provided to safely merge to the right to access a freeway off-ramp. Thus, the location of intermediate access points will need to be judiciously examined to establish a reliable and safe operational environment for interaction between the GP freeway lanes and the managed lanes.

Summary

In general, limited access managed lanes facilities offer a means to increase the capacity of a highway corridor and expedite through movements in heavily congested corridors. Limiting access, and the friction associated with weaving in and out of the managed lanes, improves the overall travel reliability of the managed lanes. Physical separation of the facilities from the GP freeway lanes creates a critical margin of safety that is especially important due to the speed differential that develops between the facilities and the GP freeway lanes. Therefore, limited access serves a dual function of making travel more efficient and safer. Although the access points tend to be focal points for crashes, due to weaving and merging; by contrast, access along a continuous, contiguous HOV lane represents an essentially infinite string of potential points of conflict as motorists weave into and out of the lane in the same way motorists change lanes in the GP freeway lanes. Nevertheless, there is an argument that this is more consistent with the freeway experience and, therefore, offers some safety due to familiarity of the driving experience. All that being said, there is general agreement that barrier-separated facilities are safer, as the number of potential conflicts characteristic of GP freeway lanes is reduced and direct speed differentials between the managed lanes and GP freeway lanes are minimized.

Limited-access does create limitations on the accessibility to locations within the corridor of travel, and the confining character of the facilities may be unsettling to some users. However, the intent of managed lanes facilities is not to support access within the corridor nor can the anxieties of individual vehicle operators be totally alleviated. More generally, the intent is to support access to destinations requiring longer distance trips in the most expeditious and reliable manner possible and provide a tool for managing traffic flow through the corridor. Therefore, limited access more correctly is seen as a method which allows longer commuter trips by employing a treatment that supports express travel.

Whereas manual enforcement of manged lanes can be an effective means of controlling access, 100% enforcement is virtually impossible. Enforcement is especially critical relative to non-barrier-separated managed lanes, which present to motorists multiple, even infinite, ingress and egress opportunities. In contrast, with regard to HOT lanes, new technologies allowing billing through license plate scanning and transponder contact have created the ability to establish more cost-effective enforcement. The remote sensing aspect of the modern technology is complementary to and supportive of free access by HOV-eligible vehicles, as Dynamic Message Signs (DMSs) and dynamic pricing provide effective tools for transportation officials to control entry and use of the HOT lanes. It should be noted that the need remains for physical enforcement practices (i.e., highway patrol) of the occupancy requirements of the HOV lane in a combined HOV/HOT facility.

Finally, it is clear the decision-making framework relating to adopting a limited-access managed lanes scenario involves numerous complex factors ranging from lane and shoulder widths to facility geometry to access to safety to convenience to cost. The objective of the evaluation must reconcile the goals and objectives of facility development with the multitude of design and operational parameters.

1.0 INTRODUCTION

The I-10/I-17 Corridor Master Plan project includes the proposal to add existing High-Occupancy Vehicle (HOV) lanes along both I-17 and I-10 segments of the Spine Corridor to create limited-access "managed lane" facilities. Managed lanes are defined by the Federal Highway Administration (FHWA) "…as freeway lanes that are set aside and operated using a variety of fixed and/or real-time strategies responding to local goals and objectives that move traffic more efficiently in those lanes."[2] During public outreach efforts several questions were raised regarding the operation, safety, and enforcement of the limited-access managed lane facility. Questions and concerns of respondents regarding this proposed action were determined to require additional information to allow the study team and citizens to make a fully informed decision. This White Paper has been prepared to provide that information.

1.1 BACKGROUND

The objective of this White Paper is to address comments and concerns raised during public outreach efforts associated with the Spine Corridor Study. Specifically, citizens attending outreach meetings were requested to respond to the following question:

> *"Currently, drivers can enter and exit the HOV lane at will. Having two managed lanes in each direction would result in limiting entrance and exit to those lanes at specific, designated points for safety. What are your thoughts on this strategy?"*

In response to the possibility of limiting entrance and exit to HOV facilities, 45% of the respondents either agreed or strongly agreed with the proposed operational concept, 18% were unsure, and 37% either disagreed or strongly disagreed. When asked for their opinion regarding expansion and modification of existing HOV facilities to create managed lanes, 58% agreed or strongly agreed, 16% were unsure, and only 26% disagreed or strongly disagreed. The responses indicate the majority of respondents were favorable to the proposed modification of the existing HOV lanes. However, less than a majority of respondents favored an action that would limit access points to the managed lanes.

Limiting access to the dual managed lanes constitutes a critical operational decision. The questions and concerns raised during the public outreach effort by those disagreeing with the concept of managed lanes and limitations on access specifically relate to enforcement, the presence of HOV lanes in general, and safety. Other issues or concerns that were voiced relate to the ability to enter and exit the limited-access facility, the need to provide greater space for the facility within the Spine Corridor, and the safety performance of the particular type of facility proposed. This White Paper has been designed to address each of the specific comments/concerns voiced as a means of providing a framework for Spine Management Partners to make an informed decision regarding the proposal to develop a two-lane limited-access HOV facility, which, ultimately, could be used to create a combined HOV lane and High-Occupancy Toll (HOT) lane.

1.2 EXISTING HOV SYSTEM

The southbound and northbound HOV lanes of I-17 occupy the median of the highway and originate at Carefree Highway. The 11-foot HOV lanes are separated, or distinguished, from the general purpose (GP) freeway lanes by a wide, solid white stripe. A 9-foot inside shoulder, which can provide refuge for a stalled or disabled vehicle, has been established between the HOV lanes and the concrete median barrier between southbound I-17 and northbound I-17. This design is maintained through the "North Stack" Interchange – I-17/Loop 101 (Pima/Aqua Fria Freeway) – to a point approximately 630 feet north of the Arizona Canal.

Right-of-way constraints at the Arizona Canal have required that the inside shoulder be narrowed (four to five feet). This new design generally is maintained south of the Arizona Canal with minor variations in the width of the inside shoulder, due principally to expanded concrete median widths forming foundations for lighting and signs and bridge structures. The southbound HOV lane ends approximately 235 feet south of Glenrosa Avenue, becoming the inside (or innermost) GP traffic lane of the four-lane freeway. The northbound HOV lane begins approximately 490 feet south of McDowell Road by means of a left merge from the inside lane of a two-lane highway section passing through the "The Stack" Interchange – I-17/I-10 West (Papago Freeway). It extends from this point to the North Stack Interchange, continuing north to Carefree Highway.

Two HOV lanes, one northbound and one southbound, are present along the entire length of I-10 within the Spine Corridor. From the "The Split" Interchange – I-17/I-10 East (Maricopa Freeway) – the southbound HOV lanes are separated from the GP lanes by a buffer delineated as two wide stripes four feet apart with a single chevron located every 30 feet. The southbound HOV lane is 12 feet wide, and the inside shoulder is 13 feet wide. The northbound HOV lane also is 11 feet wide, and the inside shoulder is 11 feet wide. The northbound HOV lane is separated by a single, wide white stripe. This design of the two HOV lanes is maintained to a point approximately 1,300 feet west of 40th Street.

East of 40th Street, the two HOV lanes generally form a symmetrical HOV facility consisting of two 4-foot buffers separating the HOV lanes from the GP freeway lanes, two 12-foot HOV operating lanes, and two 13-foot inside shoulders. This design is maintained to Alameda Drive, where there is a transition to two HOV lanes on each side of the central median barrier; one in each direction supports east- and westbound movements between I-10 and US-60/Superstition Freeway, and one in each direction supports south- and northbound travel on I-10 south of the I-10/US-60 Interchange. The symmetrical two-lane, continuous, contiguous, concurrent HOV lane facility south of the I-10/US-60 Interchange continues to Chandler Boulevard, where a second set of two HOV lanes in each direction has been established to facilitate east- and westbound travel along Loop 202, while maintaining HOV travel on I-10. The southbound I-10 HOV lane ends prior to entering the "Pecos Stack" Interchange – I-10/Loop 202 (Santan/South Mountain Freeway), and the northbound HOV lane begins in the midst of the Pecos Stack Interchange.

1.3 EXISTING HOV LANE OPERATIONS

Within the Spine Corridor, HOV facilities consist of one lane in each direction through most of its length. The HOV lanes operate as continuous, contiguous, concurrent-flow facilities that permit largely limitless entry (ingress) and exit (egress) throughout the length of the HOV lane. At any point along the length of the HOV lanes, motorists can merge directly into or out of the HOV lane from or to the inside left GP freeway lane to transition between the stream of mixed traffic in the GP lanes and the HOV lane. The essentially infinite entry/exit opportunities result in a significant degree of weaving between the HOV and GP freeway lanes, as motorists seek to access the HOV lane for travel from any given entry point (on-ramp) of the freeway to any given exit point (off-ramp). At some points, the entry or exit locations of the HOV lanes have been developed as extensions of the GP freeway lanes, allowing motorists to drive straight into or out of the lanes without an immediate transition or merge associated with the GP traffic stream, effectively creating at-grade "slip" ramps.

1.4 PROPOSED ACTION

Recommendations formulated in the Spine Corridor Master Plan include the addition of a second lane to existing HOV facilities north from The Stack Interchange to Loop 101 and south from The Split Interchange to Loop 202. This second lane is expected to increase the capacity of the corridor by increasing person throughput. In conjunction with this recommendation, limiting ingress and egress to new two-lane "managed lane" facilities to certain locations is being considered. As noted above, the term "managed lane" can refer to any lane that has restrictions or constraints on use; most commonly in the form of high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes. HOT lanes allow single-occupancy vehicles (SOVs) and other vehicles with less than the minimum number of persons required for the

[2] Section 8.0, Managed Lanes, Managed Lane Chapter for Freeway Management and Operations Handbook, FHWA, Updated Chapter, January 2011, pg 2.

HOV lane (an LOV) to operate in a dedicated, separate facility for a price. When pricing is used in this manner to "manage" entry into the HOV lanes, the SOV and LOV operators gain the advantages of an HOV lane by paying a price that usually is adjusted in accordance with the time of day and volume of traffic using the facility. This operational scenario essentially creates express lanes for longer commute trips, as points of access (ingress and egress) generally are limited, allowing higher speed of travel and fewer potential conflict with traffic flows. Modern tolling of highway use is controlled or managed by selling use privileges via transponders mounted in the vehicles or through license plate scanning technologies that allow motorists opting to use the limited-access facility to be billed by the facility operator. Therefore, should the designated managed lanes be operated as HOT lanes, free or continuous ingress and egress cannot be permitted as is the case with the existing HOV facilities in the Spine Corridor.

At the present time, only HOV lanes are proposed as part of the recommendations for Spine Corridor improvements; however, implementation of a combination facility including HOV and HOT lanes potentially exists. Creation of a HOT lane requires only the addition of technology to charge for access and the adoption of policies for operation of the lanes. For purposes of this discussion, the term "managed lanes" reflects limited-access HOV lanes, as recommended for implementation in three segments of the Spine Corridor:

Loop 101 to US-60/Grand Avenue – Southbound and northbound dual managed lanes in each direction between the proposed Direct HOV (DHOV) connector ramps at Loop 101 and a proposed DHOV connector ramps in the vicinity of US-60/Grand Avenue and Thomas Road.[3]

US-60/Grand Avenue to I-17/I-10 East Interchange (the "Split") – New southbound and northbound single managed lanes in both directions from the area of US-60/Grand Avenue and Thomas Road to the I-17/I-10 "Split" Interchange to link the managed lanes facility on I-17 with the managed lanes facility on I-10.

I-17/I-10 East Interchange ("Split") to US-60/Superstition Freeway – Southbound and northbound dual managed lanes in each direction between new connector ramps through the I-17/I-10 Split Interchange and the existing dual HOV connector ramps supporting east-west travel on the US-60/Superstition Freeway and north-south travel on I-10/Maricopa Freeway.

Implementation of managed lane facilities in the Spine Corridor has been recommended with the stipulation that the lanes may have "limited-access" as the operational configuration. Limited access means ingress/egress would be restricted to the DHOV connector ramps in much the same manner as entry of controlled-access freeways is limited through the strategic location of on- and off-ramps. Intermediate access points between the identified DHOV connector ramps have not been specified in the recommendations. Nevertheless, additional access could be incorporated provided sufficient weaving distance is available to support safe entrance to the managed lanes from a freeway on-ramp and save exit from the managed lanes to a freeway off-ramp. The new single HOV lanes recommended between US-60/Grand Avenue and the Split Interchange would operate as contiguous, continuous, concurrent-flow facilities in the same manner as the HOV lanes currently established on I-17 and I-10.

1.5 Methodology Adopted for Developing this White Paper

A quick review of the comments/concerns raised by persons concerned about the proposed action revealed a general focus on the safety of operations, enforcement, and dislike of the potential limited-access, dual managed lanes facility or HOV lanes in general. This led to an Internet search of articles, publications, and other guidance relating to safety performance of a limited-access managed lanes facilities and information relating to the operation of dual managed lanes. The Internet search resulted in identification of 75 items with direct or indirect reference to the noted issues above. Thirty-five of these items specifically focused on safety of operations, enforcement, and general desirability of such facilities have been summarized. These summaries are presented in **Attachment A**. The following two sections attempt to address the various aspects of safety of operations, enforcement, and general desirability associated with managed lanes with particular emphasis on a dual-lane, limited-access, managed lanes facility, as proposed for the Spine Corridor.

In addition, the Internet search revealed a review of Best Practices relating to the separation devised between HOT lanes and GP lanes prepared by the Texas Department of Transportation (TxDOT). This document includes a table comparing the attributes of a concrete barrier, a delineated buffer (i.e., pavement striping), and a buffer with flexible posts or pylons. This table represents a relative comprehensive evaluation of the advantages and disadvantages of these three separation treatments and has been included as **Attachment B** for reference. One additional matrix was recovered that also provides a comparison of separation types; this table is presented as **Attachment C**. In addition, a table developed by the Georgia Department of Transportation addresses emerging issues relating to the different types of barrier- and buffer-separated managed lanes; this table is presented as **Attachment D**.

2.0 Issues Associated with Limited-Access, Managed Lanes Facilities

During the public review and outreach effort conducted in support of development of the Spine Corridor Master Plan, several public comments and concerns were raised relating to limited-access, managed lanes facilities versus the current continuous-access operating conditions of HOV lanes contiguous with existing GP freeway lanes. This section attempts to address the specific comments and concerns raised by those persons relative to the proposed action to develop limited-access, dual managed lanes or the concept HOV lanes as a whole, including the operational characteristics associated with such lanes.

2.1 The Proposed Action cannot be enforced and likely not possible with current HOV enforcement strategy in the Valley – need enhanced enforcement to work (even though the limited-access points could make it easier to enforce)

Enforcement raises numerous issues when considering the type of managed lane facility to develop and implement. Whereas a paved median (i.e., inside shoulder) and enforcement area is the preferred option for new managed lane facilities, physical constraints can stifle efforts to create such areas within existing right-of-way and in place of existing HOV facilities. The literature generally concedes the lack of inside shoulders can have an adverse impact on safety and overall freeway operations. Therefore, enforcement and the degree to which there will be enforcement and the safe implementation of the adopted enforcement level are important considerations in the design and operation of HOV facilities.

The existing HOV lanes in the Spine Corridor have a striped buffer zone separating the HOV lanes from the GP freeway lanes. The buffer consists of a wide white stripe or pair of wide white stripes with periodic chevrons. The buffer is intend to maintain separation of vehicles in the HOV lanes from vehicles in the GP freeway lanes. In effect, the buffer defines an enforcement zone, i.e., motorists operating vehicles in the lanes that are not permitted (e.g., single-occupancy vehicles) can be cited for violating operating rules. Enforcement is based strictly on visual sighting of the offending vehicle/operator by an enforcement official, who then must take action to physically approach, contact (get the attention of), and direct the vehicle/operator out of the HOV lane. The existing inside shoulder of existing HOV lanes north of The Stack Interchange are too narrow to facilitate stopping the offending motorist for purposes of enforcement; therefore, the offending motorist and enforcement officer must weave through the GP freeway lanes to the extreme right shoulder of the roadway from the lane to the edge of the freeway for the issuance of a citation. The wider inside shoulder of HOV lanes south of The Split Interchange could more safely accommodate enforcement within the HOV facility, and are actively used today for this purpose.

[3] DHOV connector ramps are installed at overcrossing arterial roadways to allow direct entry and exit from the HOV lanes in the center of the freeway. DHOV connector ramps necessarily require additional freeway right-of-way to accommodate the ramp structure to and from the arterial roadway.

A study of managed-lane separation treatment options by the Maricopa Association of Governments (MAG) in 2012 concluded that enforcement of painted and buffer-delimited managed lanes generally is more difficult compared to a physically-separated facility.[4] Painted and buffer-delimited facilities allow violators to more easily move between the HOV lane and the GP freeway lanes, e.g., the offending vehicle/operator can easily move from the enforcement zone without consequences, if pending enforcement is noticed sufficiently ahead of contact with the enforcement official. Also, violators can use the HOV lane for short distances to gain advantages with respect to GP freeway lanes or use the HOV lane to pass a vehicles in the GP freeway lanes. Thus, it would be expected that painted and buffer-delimited managed lanes typically would have greater violations of restricted operational criteria than limited-access, barrier-separated managed lane facilities. This latter condition clearly raises the potential for traffic conflicts and is a highly undesirable practice. No information could be located relating to the rate of crashes associated with the different types; however, intuitively one could surmise as the number of merges occurring between the HOV facility and GP freeway lanes increases, the potential for conflicts increases.

On the other hand, barrier-separated managed lane facilities need to provide for safe, efficient, and enforceable operations by users of the facility, maintenance vehicles and personnel, and enforcement officials. As cited in the MAG report, guidance from the AASHTO's *Guide for the Design of High-Occupancy Vehicle Facilities* published by the American Association of Highway and Transportation Officials (AASHTO) states the following:

> *The absence or presence of certain roadway features can adversely affect the enforcement process as well as the safety and operational features of the facility. Physical problems may include lack of safe and easily accessible enforcement areas, absence of vantage points, lack of physical separation, and lack of passing capability for enforcement vehicles.*

Following this guidance would mean additional right-of-way would be necessary to accommodate emergency conditions, such as avoidance of a stalled or disabled vehicle by allowing a bypass path for other motorists using the facility. Ease of ready access by maintenance and enforcement personnel also is desired.

Short of additional right-of-way, the alternative is reduction in the widths of highway shoulders, enforcement areas, and even GP freeway lanes. The Ministry of Transportation of Ontario, Canada, (2017 Web Page) determined that poor safety records of some HOV facilities have resulted from adding an HOV lane where: (1) the existing roadway could not accommodate the desired buffer zone, (2) GP freeway lanes could not be maintained with adequate widths for the all other traffic, and (3) the width of the left (inside) shoulder of the HOV lane, available for emergency and enforcement, was inadequate.[5] These deficiencies resulted in a greater likelihood of collisions and reduced driver maneuverability. As a result, the Ministry adopted a policy of establishing HOV lanes on existing highways only through widening projects, instead of converting existing lanes or shoulders to accommodate the special use of an HOV lane.

The FHWA prepared a compendium of considerations associated with planning relating to the conversion of HOV lanes to HOT lanes.[6] The report highlights six different physical designs to obtain separation from the GP freeway lanes and all included a parallel emergency area (shoulder) for disabled vehicles and enforcement. The report notes that HOV-to-HOT lane conversions, which by definition include pricing from entry to exit, delineated by a painted stripe with no buffer (physical or demarcated hashed area) pose safety and enforcement issues, due to the free flow in and out of the facility of ineligible vehicles. Another design review report prepared by the Washington Department of Transportation (WSDOT) recommends a continuous inside shoulder of 14 feet associated with a HOT lane to accommodate enforcement and serve as a breakdown lane, with a minimum 2-foot opposite-side shoulder recommended to separate the travel lane from any barrier, if the ideal width is not feasible.[7] The WSDOT report also notes that an added feature might be a shoulder area (i.e., bump-out) immediately downstream of the access (entry or ingress) location to permit enforcement officers a station for observing and monitoring use of the HOT lane.

A 2004 study by the Arizona Department of Transportation (ADOT) examined issues relating to enforcement of HOV facilities.[8] It concluded that the lack of adequate enforcement would result in high violation rates. Also, legitimate carpoolers and transit users could express dissatisfaction when violators are noticed operating on the HOV lanes, and there is no enforcement. In effect, the lack of adequate enforcement would invite the HOV lanes to become GP lanes. Guidance developed for the Texas Department of Transportation (TxDOT), also in 2004, identified six characteristics to be evaluated when choosing between a buffer-separated and barrier-separated, concurrent-flow HOV lane. One of the characteristics is the "Opportunity for Enforcement Locations."[9] The report recommends 10-foot shoulders be constructed in conjunction with the HOV lanes for both types of facilities, as well as a clearly apparent painted stripe.

Guidelines developed for the California Department of Transportation (Caltrans) in 2003 sought to clarify the decision process relating to barrier-separated, buffer-separated (pavement striping), and contiguous (painted stripe) HOV facilities.[10] It clearly noted that enforcement raises numerous issues; particularly, limitations on right-of-way can preclude a paved median (inside) shoulder. Lacking an available shoulder contiguous with the HOV lane, the enforcement officer and violator must weave across the GP freeway lanes, across congested, mixed-flow traffic to the right shoulder of the freeway. This not only poses safety risks to the two vehicles and traffic in the mixed-flow GP freeway lanes, but it also is likely to result in congestion, which, in and of itself, creates operational and safety issues. This report concludes "the optimum design is the availability of adequate enforcement areas in the median. Where existing facilities do not have these enforcement areas or new facilities are not designed with them, it can be expected that enforcement on the facility will be challenging."

<u>Conclusion</u>: The literature review clearly indicates that enforcement of managed lane facilities is a challenging problem, and enforcement is more challenging with respect to painted stripe- and buffer-separated (i.e., non-barrier-separated) facilities. Active enforcement of lane violators can be disruptive of the traffic stream in the GP freeway lanes, and there always is the opportunity to avoid enforcement by getting out of the lane. A buffer-separated facility, especially with installed flexible posts or pylons, can stifle that practice to an extent, but the temptation to move into and out of a buffer-separated facility, in and of itself, raises safety issues. Safety issues arise when pylons become dislodged. In addition, pylons have been found to be an expensive traffic control measure, as they can be dislodged or ruined by vehicles traveling through them requiring frequent (90 days), regular maintenance. As a result, may transportation agencies are shying away from posts and pylons as a means of separating traffic flows.

The provision of an inside, median shoulder sufficiently wide to safely accommodate a stalled or disabled vehicle as well as enforcement actions (14 feet is preferred), raises significant issues relating to right-of-way requirements in an area that is constrained and increases development costs. Nonetheless, the recommended action in the I-10/I-17 corridor provides for sufficient shoulder width to support safe enforcement. However, it generally is accepted that a barrier-separated facility can provide a safer environment for both vehicle operations and enforcement and result in less impact on the traffic stream of the GP freeway lanes. Also, although barriers require the highest upfront expenditure, the ongoing maintenance is low compared to pylons, posts, even painted buffers.

All-in-all, with respect to enforcement, the barrier-separated facility offers the safest and most reliable method of enforcement, even precluding the need for physical contact.

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4 "Managed Lane Separation Treatment," *Managed Lanes Network Development Strategy – Phase I*, Maricopa Association of Governments, February 2012.

5 "High-Occupancy Vehicle (HOV) Lanes," Ontario Ministry of Transportation at http://www.mto.gov.on.ca/english/ontario-511/hov-lanes.shtml.

6 *A Compendium of Existing HOV Lane Facilities in the United States*, FHWA HOV Lane Performance (DTFH61-06-D-00006), prepared by Booz-Allen-Hamilton and HNTB, Dec 2008.

7 *HOT Lane Buffer and Mid-Point Access Design Review Report*, Washington State Department of Transportation, Oct 2006.

8 <u>HOV Lanes: Issues and Options for Enforcement</u>, Final Report 552, ADOT, June 2004.

9 *Guidance for Future Design of Freeways with High-Occupancy Vehicle (HOV) Lanes Based on an Analysis of Crash Data from Dallas, Texas*, Texas Transportation Institute for TxDOT and FHWA, FHWA/TX-05/0-4434-P1, May 2004.

10 "High-Occupancy Vehicle Guidelines for Planning, Design, and Operations," Caltrans Department of Transportation Division of Traffic Operations, August 2003.

2.2 Opposed to HOV lanes in general

HOV facilities have become an integral part of the transportation tool box to improve mobility and accessibility, especially in urban areas. According to the FHWA, HOV facilities "…serve to increase the total number of people moved through a congested corridor by offering two kinds of travel incentives: a substantial savings in travel time, along with a reliable and predictable travel time."[11] As the freeway network in Arizona developed over the past several decades, HOV facilities have been an important component of that expansion. Arizona currently ranks fourth in the United States in HOV system lane miles.

Because HOV lanes permit the movement of vehicles with a higher number of occupants, these facilities move significantly more people through the travel corridor during congested periods, even if the number of vehicles that use the lane is lower than on the adjoining GP freeway lanes. For example, facts presented about the HOV system in Los Angeles County indicate an average HOV lane supports the travel of 1,200 vehicles during peak periods carrying 3,100 persons. By comparison, the GP freeway lanes accommodate an average of 1,800 vehicles per lane during the same peak periods, carrying 2,000 persons.[12] The average occupancy in the HOV lane is 2.58 persons per vehicle compared to 1.11 in the GP freeway lanes.

In general, carpoolers, vanpoolers, and bus patrons are the primary beneficiaries of HOV lanes by allowing them to move through congestion; however, the use of managed lanes, in turn, frees up capacity in the GP freeway lanes, and expectations are that this new capacity will allow greater mobility for the community/region overall. Also, managed lanes are oriented to commuter traffic; this allows commuters engaged in longer trips to travel on an express facility to a destinations downstream, bypassing the more congested GP freeway lanes. Obtaining a higher average speed, while operating on the managed lanes, commuter vehicles produce lower emissions and this helps a community/region meet air quality goals. If the presence of the managed lanes also aids in reducing congestion in the GP traffic lanes, then traffic in these lanes will attain a higher overall average speed and reductions in emissions, thereby contributing to regional air quality goals. It is important to note that latent demand, the additional peak period travel occurring as congestion is reduced, ultimately will mean new vehicles will fill up the space vacated by vehicles taking advantage of the managed lanes. "This is not to suggest that increasing road capacity [through the implementation of managed lanes] provides no benefits, but generated traffic affects the nature of these benefits. It means that road capacity expansion benefits consist more of increased peak-period mobility and less of reduced traffic congestion."[13]

In addition to congestion relief and mobility improvements, separation of commuters via express travel facilities, per se, also can provide safety benefits. Reductions in congestion associated with separated lanes (especially barrier-separated lanes) aid in the safety performance of freeways. Conflicts can occur between vehicles operating in the HOV lane and GP freeway lanes, when motorists merge into and out of the HOV lane, and these actions can result in potentially serious crashes and congestion. By comparison, limited-access facilities reduce the occurrence of incidents that disrupt traffic flow in the GP freeway lanes. Generally, any disruptions of the GP freeway lanes result in extended backups and travel time delays for the large number of travelers. Disruptions in the barrier-separated lanes generally do not cause GP freeway lanes to backup (with the exception of the "rubber-necking" phenomenon).

Expeditious movement via managed lanes also provides motorists a choice of travel environments and can be an incentive for forming carpools/vanpools, which, ultimately, increases the capacity of the travel corridor. An important aspect of the modern freeway system is the degree to which roadways, originally developed for longer trips, e.g., interstate travel, now frequently are used for quick, short regional, even local trips. Because commuters often are intent on traveling several miles on their trip, as opposed to local movements between sets of on/off ramps, the managed lanes accommodate this travel more effectively and remove some through traffic from the GP freeway lanes, freeing up capacity for more localized travel and latent demand, which can come from induced travel that would not have been made and travel on alternative local streets.

Conclusion: HOV lanes make travel by HOV (e.g., carpools/vanpools, buses, motorcycles, electric or hybrid vehicles) more efficient, helping to reduce congestion in the GP freeway lanes. As a complementary alternative, HOT lanes allow motorists to opt for a travel experience at a given price. The two methods of expediting movement through corridors can aid in optimizing the transportation system and reducing or delaying the need for costly expansion projects. By increasing the effectiveness of travel through a corridor, efficiencies are attained that aid in reducing motor vehicle emissions and improving travel safety. Managed lanes are not viewed as degrading the overall mobility and safety performance of a freeway system; on the other hand, they permit transportation officials to better manage roadway capacity to create the most efficient travel system possible throughout the day, improving mobility and enhancing safety.

2.3 Dislike the CA/LA Experience

The California experience with HOV/HOT lanes is quite extensive. According to State guidelines for the planning, design, and operation of HOV lanes, the State views these facilities as an effective traffic management strategy that promotes and encourages ridesharing. Ridesharing, in turn, aids in the effort to alleviate congestion and maximizing the throughput of people in a highway corridor. As early implementers of more stringent air quality standards, the goal of managed-lane system has been to reduce congestion and improve air quality. These are the same reasons on which decisions are based in other states, and they are an integral part of Federal air quality improvement programs. Federal funding for HOV/HOT projects has been made available for the express purpose of improving air quality by reducing congestion – vehicles release less pollution when operating at optimum speeds, as opposed to idling and operating in stop-and-go conditions.

Enforcement in California is predicated on achieving optimum adherence to the rules of the HOV system, while attaining cost-effective results within the enforcement establishment. According to the Caltrans Web site, the California Highway Patrol continually monitors HOV/HOT lane use, and the goal is to keep violations below 10 percent of the traffic throughput.[14] If violations exceed 10 percent, heightened enforcement actions are implemented. While this process may seem unfair to the legitimate users of the system, it is a realistic policy decision that attains a reasonable goal while reducing enforcement costs and creating potential safety issues associated with physically contacting and stopping a violator in a stream of traffic.

The design and operation of California HOV/HOT facilities are oriented to achieving reliable travel-time savings, safety goals, and effective enforcement. Significant attention has been given to establishing design guidelines to better accommodate the weaving required to enter and exit HOV/HOT facilities. Detailed analyses are performed with the objective of ensuring facilities meet operational thresholds for the GP freeway lanes, such as merge/diverge requirements, weaving requirements, and other factors. Planning and design is focused on ensuring projects will not create new safety "Hot Spots" or increase the potential for severe or serious collisions. According to a 2012 presentation on California's Managed Lane Design Policy, the HOV facilities are becoming more boldly designated with wider pavement delineations and clarifying signage; plus, the physical enforcement process has been restructured.[15] These changes and other modifications, derived from experience with the operation and enforcement of HOV/HOT facilities in California, throughout the country, and abroad, would be incorporated in the Spine Corridor facilities, as appropriate, considering available right-of-way, costs, safety attributes, and enforcement.

[11] *Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) Lanes*, Freeway Management Program, FHWA, November 2012, at https://ops.fhwa.dot.gov/freewaymgmt/hovguidance/, retrieved 3/16/2017.

[12] *HOV Frequently Asked Questions*, Los Angeles County Metropolitan Transportation Authority – "Metro," at http://media.metro.net/projects_studies/hov/faqs.htm.

[13] Generated Traffic and Induced Travel, *Implications for Transport Planning*, Victoria Transport Policy Institute, April 20, 2017.

[14] Caltrans at CA.gov http://www.dot.ca.gov/trafficops/tm/hov.html, Retrieved 03/15/2017.

[15] *California's Managed Lane Design Policy*, PowerPoint Presentation, Joe Rouse, Division of Traffic Operations, Office of System Management Operations, Caltrans, May 2012.

Conclusion: The adaptation of the driving public to HOV/HOT facilities and the use of these facilities is a challenging process. But, there is a large body of information available to assure planners and engineers can create these facilities with the least amount of inconvenience and the highest degree of safety at reasonable cost.

2.4 THE ACCESS POINTS WILL BE A FOCAL POINT OF CRASHES

There has been extensive analyses and evaluations relating to the design and location of access (ingress and egress) points associated with HOV and HOT facilities, since these facilities in the U.S. were first developed in the 1970s. Continuous access associated with contiguous, concurrent-flow HOV facilities, such as those in the Spine Corridor, are the most common and permit a greater, even infinite, number of ingress/egress locations. These facilities provide motorists with the greatest convenience relative to decisions regarding entry to and exit from the freeway. Motorists choosing to use the HOV lane may weave over from a freeway entrance to enter at any point along its length and exit at any point, weaving across the GP lanes to a freeway way exit.

Although this ingress/egress activity can be somewhat difficult, even harrowing for some drivers, generally it occurs with relative success. Information available through the Ontario Ministry of Transportation (2017) indicates that the poor safety records related with buffer-separated HOV facilities, which add a similar degree of separation as provide for the HOV lanes in the center of I-10, primarily resulted from shoehorning facilities into existing corridors and not driver competence.[16] Inadequate buffer zones, narrow GP lanes, and inadequate width of the median (inside) shoulder for emergency and enforcement (not the case on I-10, but particularly relevant for I-17 HOV lanes) were identified as the principal reasons for safety problems. As noted earlier, the Ministry, therefore, adopted a policy of incorporating HOV lanes only through widening projects that permitted attaining the latest highway design standards.

Investigations in Texas (2003) examined a variety of techniques and measures for expediting traffic flow in freeway corridors. Although the Texas study asserts "the characteristics that matter most to the driver are speed of travel, safety, comfort, and convenience," little information is provided regarding the safety of any of the investigated HOV facility types, and no safety information is provided relative to the design criteria for a managed lane facility.[17] Unfortunately, specific, quantifiable information regarding the safety experience at access points has not been a focus of the many studies conducted to date. Nevertheless, the Texas investigations provide some salient points regarding safety that generally are supported by other available studies.

Available studies generally support the notion that limited-access, barrier-separated HOV/HOT facilities are safer than continuous, concurrent-flow facilities. The safety issues of such facilities primarily are associated with the design of access points and lane configurations. While a study for Caltrans in 2009, comparing continuous- and limited-access facilities, concluded "…HOV facilities with limited access offer no safety advantages over those with a continuous access,"[18] the report also notes that inside, median shoulders greater than eight feet in width resulted in "…significantly lower collision rates, regardless of access type." In addition, the study team found collision rates were "markedly higher" for a limited-access HOV facility with a combination of (1) short ingress/egress lengths and (2) close proximity to the nearest on/off ramps.

Thus, the occurrence of crashes appears to be more a function of facility design and integration of access points within the freeway, rather than the facility operation in and of itself. For example, the Texas Manual found that wider facility envelopes are associated with reduced crashes on freeways at all severity levels and all fatal and injury severity levels, and there was an increase in the number of crashes with an increased number of access points.[19] Also, in the 2009 Caltrans study, it was found that, although neither facility provide any safety advantage, "maintaining adequate shoulder and total [facility] width is essential…."[20] Three key conclusions from this study are:

- Maintenance of adequate shoulder width is essential;
- Optimize the length of ingress/egress sections (higher collision rates were found to be associated with the short access sections, i.e., slip ramps);
- Optimize distances between ingress/egress locations and freeway on/off ramps – "…locating access areas in close proximity to on/off ramps should be avoided."

The findings of studies in Texas, California, and Ontario, affirmed, in part, an earlier study by the Washington Department of Transportation (WSDOT) that addressed buffer widths (4-foot buffers preferred, 2-foot minimum), the need for a continuous inside (median) shoulder (14 feet is preferred to accommodate safe enforcement), and minimum lengths for access or slip ramps (500 feet).[21] The later MAG White Paper (2012), prepared to address separation approaches for HOV/HOT lanes, concludes that, assuming all other factors to be equal (e.g., mix and density of traffic, roadway geometrics, access locations, etc.), barrier separation is safer than non-separated treatments.[22] It also notes that safety associated with all treatments, in terms of both crash occurrence and severity, is influenced by the length and location of access locations and the speed and density of traffic streams. A finding similar to that made by the TxDOT and the Ontario Ministry of Transportation.

Conclusion: As late as 2012, a White Paper prepared by MAG found no readily available information in the form of studies or databases to aid in identifying specific causal factors of crashes in relation to the various design treatments. Although only generalized inferences may be drawn from available information, the White Paper concluded a consensus apparently exists that, all things being equal, barrier separation is safer than non-barrier treatments, specifically painted and buffer-delimited treatments. This conclusion is affirmed by the FHWA at its Frequently Asked Questions Web site for Freeway Management, where it is stated that "the safest HOV lanes are those that are physically separated from the adjacent lanes with a concrete barrier," and separation also creates greater safety for traffic in the GP freeway lanes.[23]

Thus, safety at the access points for a limited-access, barrier-separated facility is more a matter of applying the latest knowledge and experience, i.e., best practices, in the design of the facility, specifically the location of access points, the location of these points relative to on/off ramps of the freeway, and the length of access or slip ramps. GP freeway lanes providing direct entry to and exit from the limited-access, barrier-separated facility, along with adequate signage and lighting, are viewed as significantly enhancing the safety performance of the facility and the interaction of facility users with traffic in the GP freeway lanes. The speed differential of vehicle operating in the managed lanes compared to likely congested GP freeway lanes would call for special consideration of signage and facility design to maximize the opportunity for safe transitions. In addition, as noted earlier, wide (14 feet) median (inside) shoulders are considered to be critical to facility performance and enforcement and the number and location of access points would need to reflect access requirement of first responders.

Limited information is available related specifically to dual HOV lane facilities, as these are relatively non-existant in the United States. Therefore, the actual design of the recommended dual managed lane facilities and the number and locations of access points would need to be the subject of modeling and traffic studies to ascertain: traffic volumes in the corridor and demand for the managed lanes; frequency of access and demand along the

[16] "High-Occupancy Vehicle (HOV) Lanes," Ontario Ministry of Transportation at http://www.mto.gov.on.ca/english/ontario-511/hov-lanes.shtml, retrieved 03/09/17.

[17] Interim Manual for Managed Lanes, Texas Transportation Institute for TxDOT, Report 4160-14 (FHWA/TX-04/4160-14), October, 2003.

[18] Safety Performance of High-Occupancy Vehicle (HOV) Facilities: Evaluation of HOV Lane Configurations in California, Safe Transportation Research & Education Center, Kitae Jang, et al, January 2009.

[19] Ibid. Interim Manual for Managed Lanes.

[20] Ibid. Safety Performance of High-Occupancy Vehicle (HOV) Facilities.

[21] Ibid. *HOT Lane Buffer and Mid-Point Access Design Review Report.*

[22] Ibid. Managed Lane Separation Treatment.

[23] *Summary of Key Points RE: HOV Ins*, "Frequently Asked HOV Questions at FHWA Freeway Management Program Web site, https://ops.fhwa.dot.gov/freewaymgmt/faq.htm, retrieved 2017

Spine Corridor; and weaving and queuing dynamics at the ingress and egress points. All this must be considered with the constraints on right-of-way and the degree to which the community agrees with any expansion of right-of-way to accommodate the proposed improvements. As project development proceeds, safety assessments also will be conducted to determine more factually the risks of crashes at key locations within the Spine Corridor, including access points.

3.0 OTHER QUESTIONS/COMMENTS

In addition to the comments and concerns raised by those less favorably disposed to the proposed action, the following additional topics were submitted in various forms. This section seeks to respond to these topics so Spine Management Partners and general public can make a more informed decision regarding the design, configuration, and operation of proposed managed lanes.

3.1 RELATIONSHIP OF RESTRICTED ACCESS POINTS AND TIME OF DAY USE OF HOV?

The provision of a dual managed lane facility may include installation of a barrier to physically separate the HOV lanes (and potential future HOT lanes) from the GP freeway lanes. The purpose of the barrier is to restrict entry and exit to specific locations. This generally is viewed as a more desirable and safer operating configuration, as noted earlier, although the latest guidance from FHWA that Utah and Minnesota have incorporated "…a more continuous access policy…" that increases ingress and egress opportunities.[24] Regardless of the method of separation, access control is critical to the cost, operational, safety, and enforcement trade-offs associated with managed lanes. The usual and customary use of the facility by carpools/vanpools, buses, motorcycles, and electric/hybrid vehicles, as permitted by HOV policies, would not be hampered. HOV lane-eligible users would be allowed unrestricted access throughout the day. Similarly, SOV users are not allowed to use the facility during specified times.

Should a decision be made to incorporate HOT lanes in conjunction with the dual managed lane strategy, tolling operations and policies associated with the HOT lane likely would include dynamically-adjusted toll rates, based on real-time traffic conditions. As the volume of traffic increases in the managed lane facility, the toll would be increased to assure the facility would be able to operate at an acceptable level of service (LOS). Facility LOS would be determined in accordance with real-time observations of traffic and policies established for the facility. Generally, congestion within the freeway corridor during peak travel periods means there would be increased use of the HOV/HOT facility; therefore, peak periods would have the highest toll.

Conclusion: Restricted access points associated with limited-access facilities are managed operations over a 24-hour period. Generally, limited-access facilities associated with tolling are never opened to GP traffic. That is to say, control of limited-access tolling facilities is not relinquished to GP traffic, as is done with HOV lanes currently in the Phoenix area. Recent interest has arisen for continuous access, but issues of pricing, safety, and enforcement become more complex. Signage and driver awareness become more critical with restricted access, as decisions to access a managed lanes facility may be inadvertent resulting in an undesirable maneuver to return to the GP freeway lanes.

GP freeway traffic can make use of the limited-access facility through established ingress and egress points, in accordance with restrictions on use applied throughout the day. Restrictions on use can be modified throughout the day through DMSs, based on the volume of traffic in the corridor. Time-of-day use would only be appropriate with managed lanes that operate much the same as the existing HOV lanes in the Phoenix metropolitan area. These facilities permit access at infinite points and function in restricted operation only during the peak periods and do not impose a charge or toll.

3.2 POTENTIAL FOR ONE MILE ACCESS POINTS GIVEN THE EXISTING ONE-MILE SPACING OF TIS

The inherent operational philosophy associated with development and implementation of managed lanes is to create a reliable facility for trips that (1) expedites commuter travel over longer distances and (2) can be viewed as preferable to the congested GP freeway lanes. Because a good portion of urban freeway usage has become associated with localized movements of a few miles (even one mile or less), separating commuters engaged in longer trips brings relief to the GP freeway lanes of the burden of what essentially can be considered to be through-traffic movements. Because the managed lanes are not established to accommodate shorter distance trips, which do occur (e.g., Glendale Avenue to Camelback Road in the Spine Corridor), access points do not need to be as frequent as the traffic interchanges (TIs). In fact, FHWA notes that "access spacing of two to three miles is common for most restricted access treatments."[25] Nevertheless, ADOT studies have suggested that barriers limiting entrance and, particularly, exit from managed lanes can be a discouraging aspect for commuters, when exits are not convenient to their desired destination.[26]

The design and location of access points (ingress and egress) not only affects user convenience but, also, safety and operational performance of the facility. Enforcement capabilities also can be affected. Another key design consideration for access points (ingress and egress) on a limited-access, barrier-separated managed lane facility is adequate length of the transition or weave zone to support ingress and egress. The weave zone requires an adequate distance between the access point and on/off ramps of the freeway to permit movements into and out of the HOV/HOT facility without impeding movement onto and off of the freeway via on- and off-ramps.

Figure 3.1
Photo of Access Point for Access-Restricted

Source: Section 8.0, Managed Lanes, Managed Lane Chapter for Freeway Management and Operations Handbook, FHWA, Updated Chapter, January 2011.

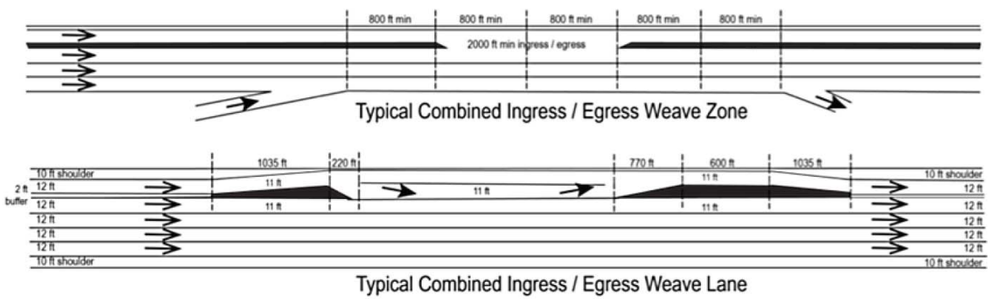
Figure 3.3 shows two plan views for a combined ingress/egress access points. It is clear from **Figure 3.3** that such configurations would occupy much of the space between TIs. The simple ingress/egress weave zone would require 2,400 feet. With modern freeway on- and off-ramps extending 1,200 feet, the weave zone would not be readily accessible from the nearest on- or off-ramps, because there would be insufficient distance to weave through three lanes of traffic. The more complex ingress/egress weave lane would occupy 5,660 feet (assuming a 2,000-foot minimum ingress/egress point, although some sources shows this as little as 1,500 feet).

[24] *Priced Managed Lane Guide*, Chapter 6. Design, Tolling and Pricing Program, Federal Highway Administration at https://ops.fhwa.dot.gov/publications/fhwahop13007/pmlg6_0.htm.

[25] Ibid. Section 8.0, Managed Lanes, pg 38.

[26] HOV Lanes: Issues and Options for Enforcement, Final Report 552, ADOT, June 2004, pg 14.

Figure 3.2 Plan Views of Typical Combined Ingress/Egress Access Points

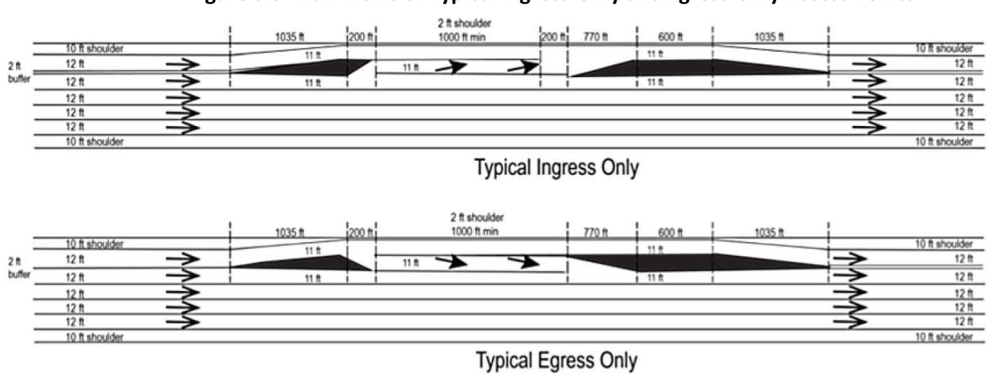


NOTES: The Weave Zone plan does not show an inside shoulder, which would be very desirable.
A 14-foot inside shoulder is preferred for safety of operations, incident response, and enforcement.

Source: Caltrans Traffic Operations Policy Directive, 2011, presented in *Priced Managed Lane Guide*, Chapter 6. Design, Tolling and Pricing Program, Federal Highway Administration at https://ops.fhwa.dot.gov/publications/fhwahop13007/pmlg6_0.htm.

Figure 3.4 shows two plan views of separate ingress and egress access points (refer to **Figure 3.2**). The ingress-only access point accommodates entry to the managed lane by way of a 2,170-foot slip ramp, and the total length of the managed lane bypass is 4,840 feet in length to accommodate the merge. The total length of the egress-only access point is slightly less at 4,640 feet with a 1,970-foot slip ramp.

Figure 3.3 Plan Views of Typical Ingress-Only and Egress-Only Access Points



NOTES: A 14-foot inside shoulder is preferred for safety of operations, incident response, and enforcement.

Source: Caltrans Traffic Operations Policy Directive, 2011, presented in *Priced Managed Lane Guide*, Chapter 6. Design, Tolling and Pricing Program, Federal Highway Administration at https://ops.fhwa.dot.gov/publications/fhwahop13007/pmlg6_0.htm.

Thus, while intermediate access points are doable, there location and design will depend on "…the existing and planned roadway geometrics and the amount of traffic expected to use the opening. In all cases, openings should be located and designed in a way that will not produce adverse impacts to the managed lanes and the parallel highway lanes. The locations of at-grade access openings need to be closely coordinated with highway entrance and exit ramps and allow adequate room for motorists to complete weaving movements when moving between the general-purpose and managed lanes and an entrance or exit ramp."[27] That is to say, the spacing of access points should not be located immediately downstream from a freeway on-ramp or immediately upstream from a freeway off-ramp. The preferred location for access is in a portion of the freeway with the lowest potential for congestion and between on- and off-ramps.[28] This positioning provides motorists ample time and space to complete weaving maneuvers through the GP freeway lanes to access the managed lanes from the on-ramp and exit to an off-ramp. With TIs located every mile, the number of intermediate access points necessarily will be limited to avoid traffic conflicts and tie-ups resulting from dangerous weaving actions. The transition or weave areas would need to be strategically located to coordinate with origins and destinations within the Spine Corridor, while taking into consideration weaving requirements.

Conclusion: As noted earlier, the objective of managed lane facilities is to increase person throughput via a reliable means that is viewed as favorable to congestion. Determining the locations for access points (ingress and egress) necessarily must follow careful examination of corridor travel dynamics as well as major points of origin and major destinations. Longer trips are favored for managed lanes, as limited-access reduces friction, and higher travel speeds reduce travel time. Attempting to identify at this time how many access points should be provided along the Spine Corridor would be an arbitrary action, at best. No specific conclusion regarding access points along the Spine Corridor relative to access points in California is justified based on the information in this White Paper. Determining the number and locations for any intermediate access points (ingress and egress) necessarily must follow careful consideration and examination of: the objectives of the project; travel reliability; travel patterns; traffic volumes; potential disruptions of traffic flow; concentrations of major trip origins and destinations; weaving associated with each access point; geometrics of the freeways, especially the presence of horizontal and vertical curves (horizontal curves being more problematic); as well as connectivity with regional origins, destinations, and other routes of travel.

3.3 PERCEPTION THAT THE RESTRICTED ACCESS POINTS WILL NEED MORE PHYSICAL SPACE.

There is no doubt that managed lanes require space within the travel corridor in addition to the GP freeway lanes and any frontage roads. As noted earlier, the preference for a wide, inside shoulder for emergency and enforcement reasons means adequate space must be allocated to the managed lane facility while maintaining physical capacity of the GP freeway lanes, freeway on- and off-ramps, and frontage roads (if present) as well as an insider shoulder for breakdowns and emergency in the GP freeway lanes. Although limited right-of-way may present challenging design solutions, introduction of a managed lane facility may, on the other hand, allow a community to postpone expansion of an existing freeway facility to add capacity.

Depending on the adopted design and location of access points, there may or may not be a need to expand right-of-way. **Figure 3.2** above shows an access point that is, in effect, a slip-ramp to an HOV lane (refer also to **Figure 3.4**, Ingress-Only). A subsequent slip-ramp of similar design would be provided at an intermediate exit along the length of the managed lanes to facilitate merging into traffic in the GP freeway lanes (refer to **Figure 3.4**, Egress-Only). The locations of intermediate access points (ingress or egress or both) would be determined during detailed planning and operational studies for a managed lane facility. As shown in **Figure 3.3**, both ingress and egress can be at the same location. Both types of access would require widening the freeway in the area of the access point. It should be noted that intermediate access locations are not included in the Spine Corridor Recommendations Key Map; it is not known whether intermediate access points are being contemplated for the managed lanes facility. As noted earlier, DHOV ramps are contemplated, and these ramps likewise would require space within the corridor.

Conclusion: The final design and configuration of the limited-access facility will depend on yet to be accomplished traffic and travel pattern studies, design studies, engineering studies. As proposed in the Spine Corridor Recommendations Key Map, access to the Spine Corridor managed lane facilities would occur at DHOV connector ramps at the ends of three segments. DHOV connector ramps would require additional physical space. Intermediate access points also would require additional physical space. However, it has not yet been determined whether or not the additional physical space would require acquisition of additional right-of-way. Conceptual and preliminary design studies must be accomplished to fully address this issue.

3.4 AAVAILABILITY OF RESEARCH INDICATING THE LIMITED-ACCESS MODEL IS ACTUALLY SAFER

The specific question of the safety associated with access points created for a limited-access managed lane facility has been addressed in a previous section. The most recent guidance relating to development of managed lanes and the overall safety of these facilities is contained in the FHWA Handbook. The FHWA Handbook suggests safety can be a function of HOV/HOT lane operating scheme.[29] The Handbook notes that part-time managed lane operations that revert to GP freeway lanes during non-peak periods need to look and function like the GP freeway lanes. The Handbook states that managed lanes that operate part-time, i.e., eligibility restrictions are in place only during specific periods, should be continuous, as the lane serves the general traffic flow during open periods. This is the case relative to HOV lanes established in the Phoenix metropolitan area.

The part-time operational configuration requires careful and extensive signing and messaging to assure motorists are fully informed of the time-of-day restrictions. Nevertheless, contiguous, continuous-access, concurrent managed lanes can be opposite to driver expectancy and adversely affect safety of traffic operations. That is to say, the presence of such lanes can create confusion for motorists, who may be unfamiliar with the striping and delineation of the specialized lane. This condition provides one argument for barrier-separated, limited-access managed lane facilities and elimination of the time-of-day use scenario.

The Handbook notes that full-time managed lane operations can be either open or entry can be restricted to designated locations in the case of buffer-separated facilities, particularly facilities that employ flexible posts or pylons within the buffer. The reference here is specific to HOV lanes and not HOT lanes. Approximately 60 percent of the HOV lane-miles in the U.S. operate under unrestricted or open access. The remaining facilities incorporate access control with designated or delineated entry zones to accommodate necessary weaving and transition between GP freeway lanes and the HOV lane. The Handbook notes that some access-restricted managed lanes in Southern California are being converted to accommodate continuous-access. At the same time, some HOV lanes elsewhere are being converted to restricted-access to accommodate the charging and enforcement of tolls for use. The Handbook indicates various studies of the safety associated with managed lane operations "suggest" that both unrestricted- and restricted-access facilities "…can be safe and function well."

Nevertheless, the question of crash modification factors (CMFs) certainly is worthy of note. The AASHTO *Highway Safety Manual* (HSM) includes a method for quantitatively gauging the effectiveness of various safety countermeasures (e.g., access management, lighting, and signage). The CMFs are useful in estimating the expected change in the number of crashes (average) at a particular site or locale subsequent to implementation of a safety countermeasure. In a guide prepared for the Pennsylvania Department of Transportation (PennDOT), appropriate CMFs were identified to aid the Department in evaluating safety performance of proposed changes to the highway

[27] Ibid. *Priced Managed Lane Guide*, pg 5.

[28] Ibid. *California's Managed Lane Design Policy*.

[29] Section 8.0, Managed Lanes, Managed Lane Chapter for Freeway Management and Operations Handbook, FHWA, Updated Chapter, January 2011, pg 31.

and street network in the State. In this guide, the authors point out that the CMF is an estimate "obtained from statistical analysis of reported crash data."[30] Further, the true CMF is noted to be "unknown," as there always is some error involved in statistical analysis.

That being said, the importance of having data analysis to support decisions cannot be understated, and the CMF value for converting continuous-access HOV lanes to limited-access facilities was determined by the study team to be 1.74 (less than 1.0 is better). Nevertheless, it must be pointed out that the goal of conversion and the objectives of limited-access facilities, in general, is not safety. The intent of creating a limited-access facility is not to create a safer operating environment, but to create a more efficient roadway or travel corridor by increasing capacity. This is not to say that safety is not a concern, only that safety is not the sole concern. In fact, many elements of the transportation infrastructure must be considered, reviewed, and thoroughly examined within the limits of knowledge and analytical capabilities prior to adopting one particular highway treatment over another. For example, signage, lighting, barrier design, shoulder widths, and other roadway features must be evaluated and integrated to create modern highway facilities. The PennDOT CMF Guide states a single CMF may be applied to a particular site "…to estimate the impact of a single countermeasure" (i.e., safety-oriented improvement) and "…to a particular site to estimate the impact of multiple countermeasures applied simultaneously."[31]

Therefore, the safety aspects of the limited-access managed lanes clearly must be recognized and designs incorporating multiple safety-related improvements, as cited above, must be developed to mitigate potentially hazardous operating conditions. However, safety cannot be the prime determinant for selecting any given treatment. As pointed out in an FHWA publication, *Safety Implications of Managed Lane Cross Sectional Elements*:

> *Managed lanes (ML) can provide safety and operational performance benefits over general-purpose (GP) facilities, but the managed lane strategy must be appropriate for the intended user group. Specific benefits in crash reduction seen at one facility do not necessarily translate to another facility, so the selected strategy must account for the conditions unique to a particular facility.*[32]

Addressing crashes at access points of a managed lane facility, the FHWA publication notes that crashes at freeway access points are similar to crashes common to intersections of surface streets. This similarity derives from comparable operating circumstances, i.e., vehicles re-entering the freeway GP lanes are intersecting with an established stream of traffic. Likewise, vehicle operators at these intersections can be tentative or inappropriately enter the traffic stream, resulting in rear-end crashes. Thus, the issue of safety with regard to access points must be addressed in the same manner as other operational aspects of the vehicle operating environment, which is a normal and customary practice of transportation planners and highway engineers. Hence, it will be important that the following be the primary guide for understanding and mitigating the potential for access point crashes:

> *Traffic volumes, the type of access and separation provided, and proximity of managed lanes access to general-purpose entrance and exit ramps may all have an effect on crashes, and these effects may vary from one facility to another.*[33]

It seems important to reiterate in the discussion of overall facility safety that there two very different operational philosophies associated with unrestricted- and restricted-access with respect to managed lanes:

Unrestricted, or Continuous Access – Allowing open or continuous access is adopted with the intention of (1) providing greater convenience and flexibility of use by motorists throughout the day and (2) allowing drivers to address weaves and merges to the managed lane (normally, a HOV lane) in the same manner as operating within GP freeway lanes.

Restricted or Controlled Access – Controlling entry and exit of the managed lane facility generally has the intent of establishing conditions allowing implementation of a specific policy objective, such as tolling or addressing specific geometric or operational issues associated with the freeway. Restricted access also seeks to reduce unnecessary weaving and/or the frequency of weaving, discourage short distance trips in the managed lanes, and reduce opportunities for queue-jumping under congested conditions.

An important aspect of managed-lane facilities is accommodation of longer distance travel, essentially separating through traffic from more localized traffic that has become a common use of today's urban freeways. Some communities in Texas have, in fact, created separate, grade-separated express facilities parallel with GP freeway lanes with no exits for several miles to encourage commuters to leave the GP freeway lanes, which offer access to intermediate destinations.

The FHWA Handbook notes that the vast majority of managed-lane facilities operating today have been designed for and established within existing freeway corridors, often based on constrained design settings peculiar to the corridors.[34] As such, planning and development of the managed-lane projects have included difficult trade-offs and compromises. Still, it concludes, "since all have operated safely and perform reasonably well in meeting their stated operational objectives, there are few 'best practices' that are nationally transferable."[35] Even so, there is a reasonable body of knowledge upon which to draw in developing managed lanes, especially when managed lanes are proposed as a component of major corridor modifications and widening.

With direct reference to the safety of limited-access managed lanes, the FHWA Handbook suggests the speed differential between managed lanes and GP freeway lanes is the most important aspect to consider.[36] Guidelines for design and development have for many years advocated barrier separation as the safest operating configuration for concurrent traffic streams. Still, all other things being equal, barrier-separated managed lanes have not attained a better over safety record compared with non-separated facilities with lanes designated through pavement markings. Nevertheless, throughput, demand, and cost become factors when considering tolling and the need for barrier-separated facilities.

Continuous-access, concurrent managed lanes cannot safely support the speed differential relative to GP freeway lanes required to justify charging for use. The FHWA Handbook suggests 30 years of experience indicates this type of facility can only provide an average travel speed of 40 miles per hour compared to the typical 20 miles per hour for GP freeway lanes. Therefore, it states "physical separation may be preferable for facilities that incorporate tolling to ensure that violation levels are kept to a minimum and the integrity of the facility is maintained."[37] That is to say, pricing toll lanes needs to assure the purchaser that facility will deliver a high quality of service, i.e., the speed of travel and travel time more than competes with GP freeway lanes and the typical HOV lane.

As noted earlier, limited-access, managed-lane facilities commonly incorporate access spacing of two to three miles. The proposed action would provide considerably less flexibility, incorporating DHOV ramps at select locations, and only the potential for intermediate access points. The defined segments are several miles in length; therefore, there could be one of more access points within the segments. The important point is that the frequency of potential conflict points associated with the existing contiguous, continuous-access, concurrent HOV lanes would be reduced significantly by directing entrance into and exit from the limited-access managed lanes along extended lanes. This

[30] *Pennsylvania CMF Guide*, Gayah, et al, Department of Civil and Environmental Engineering, Pennsylvania State University, for PennDOT, August 2014.

[31] Ibid. pg. 4.

[32] *Safety Implications of Managed Lane Cross Sectional Elements*, Chapter2, Literature Review, Federal Highway Administration, FHWA-HOP-16-076, December 2016, pg 1.

[33] Ibid.

[34] Ibid. Section 8.0, Managed Lanes, pg 34.

[35] Ibid.

[36] Ibid. Section 8.0, Managed Lanes, pg 37.

[37] Section 8.0, Managed Lanes, Managed Lane Chapter for Freeway Management and Operations Handbook, FHWA, Updated Chapter, January 2011, pg 38.

would permit greater time, with adequate signage, for vehicle operators to gain access to the entrance lanes and merge back into the GP traffic lanes upon exiting the facility. In effect, at-grade entrance and exit slip ramps could be created, providing adequate time for transitioning from and reentering the GP freeway lane immediately adjacent the managed lane facility. This would aid in sustaining the speed of the managed lane facility and allow motorists more time to synchronize with the speed of the GP freeway lanes. Clearly, the matter of safety with regard to limited- or restricted-access managed-lane facilities depends largely on the design of the facility. There is now available ample guidance derived from the experience in many communities to aid in developing limited-access, managed-lane facilities that can be as safe or, potentially, safer than contiguous, continuous-access, concurrent managed lanes. Most studies conclude that barrier-separated managed lanes are safer than contiguous, continuous-access, concurrent managed lanes. Guidance from several studies suggest safety performance associated with limited-access, managed-lane facilities is most closely associated with access points. Therefore, entry and exit of the facility as well as adequate signage and lighting is of paramount importance. The speed differential, especially at facility exits, heightens the potential for vehicle conflicts and actions to mitigate the effect of this factor likely would reduce the potential for crashes.

4.0 CONCLUSIONS

The following guidance may be generally deduced from the information provided in this White Paper. The conclusions cited below, however, should not be construed to be recommendations for specific action, as there are many factors that still need to be considered with specific focus on the three segments of the Spine Corridor and the overall functioning of the corridor from Loop 101 to Loop 202.

There are no "overarching" reasons(s) for not adopting the limited-access, managed lanes solution. The objectives of the project are most important, and safety is one aspect of the project – an aspect that has not been definitively found to be better or worse with limited-access managed lanes. The statements below attempt to synthesize matters of apparent concern regarding implementation of a barrier-separated, limited-access, managed lane facility.

Will barrier-separated, limited-access, managed lanes result in greater person throughput, i.e., increase the capacity of the corridor?

The number of persons using the managed lanes and the volume of these vehicles results in greater passenger trips through in the corridor. Managed lanes generally are perceived as providing a faster, safer travel experience, due to the exclusivity of the facility and the reduction of friction caused by congested traffic conditions. Attracting (not diverting) motorists to the managed lanes relieves congestion in the GP freeway lanes, at least in the short-term. Some congestion may reappear in the GP freeway lanes, principally due to latent demand occupying space released by motorists opting for the managed lanes. In the long-term, more person throughput is achieved in the corridor, as motorists operating vehicles with more passengers per vehicle are motivated to use the managed lanes and motorists traveling on other routes (e.g., arterials) are motivated to take trips on the GP freeway lanes being viewed as less congested.

Will safety be enhanced or negatively impacted?

Different safety concerns are associated with the two different types of managed lanes: contiguous, continuous HOV lanes and barrier-separated, limited-access, managed lanes (i.e., HOV/HOT lanes). Limited-access managed lanes largely eliminate direct conflicts with GP freeway lanes; whereas, there are an infinite number of potential collision points associated with contiguous, continuous HOV lanes, as characterized by vehicles frequently transitioning between the HOV lanes and the GP freeway lanes. The managed lane facility generally will be less congested, devoid of lane weaving characteristics of the GP freeway lanes, and provide a safer operating environment. This aids in minimizing the potential for vehicle conflicts. Short of an extremely strong collision that would send a vehicle beyond the barrier, a managed lanes facilities poses no significantly greater safety risks to GP freeway lanes.

The level of safety in the corridor under both types ultimately is determined by the final design and operational configuration of the new combination of managed lanes and GP freeway lanes. That is to say, crashes will occur in the managed lanes, separated or not separated, and in the GP freeway lanes, because, in reality, all lanes are supporting the movement of traffic. Crashes not occurring within the managed lanes facility generally would be associated with the ingress and egress points, where weaving and merging would occur. However, ingress and egress slip ramps formed of the most inside lanes of the freeway would assist in transitions out of and into GP freeway lanes, reducing the potential for and severity of conflicts. Wide inside shoulders would enhance the safety for vehicles operating in both types of managed lanes, as the shoulders will provide a relatively safe location for emergency stopping, enforcement, and clearing of traffic incidents.

Will the managed lanes provide a reliable alternative to travel in the GP freeway lanes?

A primary objective of creating managed lanes is to provide users with a more reliable and expedient travel environment compared to congestion generally characterizing heavily traveled freeway corridors. If reliability and expediency of travel are considered more desirable than using congested GP freeway lanes, officials succeed in relieving pressure on the GP freeway lanes. Generally speaking, based on the large number of communities in the U.S. and outside the U.S., managed lanes are considered to be successful in increasing the carrying capacity of a corridor and a reasonably safe method of enhancing the degree of control over traffic flow in a corridor. Managed lanes which restrict entry and limit opportunities for exit, are considered more reliable than unrestricted HOV lanes, as traffic volume can be controlled and attention to the vagaries of congestion are less a factor for motorists. Contiguous, continuous, concurrent HOV lanes allow almost infinite opportunities for entry and exit through the length of the facilities. However, GP freeway lanes are susceptible to being bogged down easily and quickly in response to the slightest aberration in the flow (e.g., a tapped break, a motorist slowing to merge to another lane, a crash that affects all lanes), and this can directly impact flow in the HOV lanes.

Is time-of-day use of a limited access managed lanes facility an option?

The decision to have an operational managed lane generally would require creation of a limited-access facility. However, there are some recent cases in which greater, even continuous, access has been adopted for managed lane operations in particular. HOV lanes generally have been used to accommodate peak-period travel, and setting the number of persons required in a vehicle to allow use of an HOV lane is a form of traffic management asserted by the community. HOT lanes provide a more nuanced approach to traffic management in that the price for accessing/using HOT lanes can be modified, as necessary, to minimize congestion within the HOT lane facility and optimize operations in the corridor overall. This usually requires full control of the facility throughout the day and assures motorists engaged in longer trips reliable and expedient travel. At times, these lanes will be underutilized, but a primary focus is to assure availability of the facility, minimize the number of access points, and reduce confusion regarding use.

How many access points would be appropriate?

This White Paper cannot purport to establish the frequency or location of access points. This matter must be determined after consideration of numerous physical, operational, and community factors, including, but not limited to:

- Traffic volumes along the Spine Corridor – access points are best located where heavy traffic volumes or hazardous traffic conditions (e.g., curve) are not present;
- Superelevation – Horizontal curvature is particularly critical, due to line-of-sight restrictions (vertical curvature is not as important, but still is a factor to consider);
- Locations of origins and destinations – Mostly oriented to support commutes to Central Business Districts (CBDs) or other employment or activity centers/concentrations;
- Limited access, managed lanes serve to support direct travel between key destinations and providing intermediate access must weigh the level of demand at proposed locations against the potential effects on the operational reliability of the facility;
- Access for response to incidents – Emergency stopping and crashes will occur within a limited-access facility, requiring access by emergency vehicles, which may require additional restricted access points to assure timely response from appropriate entities;
- Pricing decisions – Pricing according to distance traveled typically is associated with tolled facilities, and additional access points will require more complex pricing formulas, more complex ETC equipment and arrangement, alteration of pricing decisions aimed at controlling traffic volume within the facility.

ATTACHMENT A

REVIEW/SUMMARY OF KEY SAFETY POINTS IN SELECTED LITERATURE

REVIEW/SUMMARY OF KEY SAFETY POINTS IN SELECTED LITERATURE

HIGH-OCCUPANCY VEHICLE (HOV) LANES (2017)

["High-Occupancy Vehicle (HOV) Lanes," Ontario Ministry of Transportation at http://www.mto.gov.on.ca/english/ontario-511/hov-lanes.shtml, retrieved 03/09/17]

A striped buffer zone is intend to maintain separation of vehicles in HOV lanes from vehicles in the GP freeway lanes. Barrier-separated HOV facilities require additional right-of-way or result in reduction in the widths of highway shoulders, enforcement areas, and travel lanes. A painted buffer is more flexible than a fixed, physical barrier and permits a greater number of ingress/egress locations. The buffered HOV facility is more convenient for motorists in that all freeway exits are accessible. Also, a painted buffer can be more quickly adjusted to respond to changes in traffic patterns and volumes.

Ontario's HOV lanes include a striped buffer to separate the HOV lane from the GP freeway lanes. A left shoulder is included for optimum safety. The Ministry determined that poor safety records of some HOV facilities in other jurisdictions had resulted from adding an HOV lane where: (1) the existing roadway could not accommodate the desired buffer zone, (2) GP freeway lanes could not be maintained with adequate widths for the all other traffic, and (3) the width of the left shoulder of the HOV lane, available for emergency and enforcement, was inadequate. These deficiencies resulted in a greater likelihood of collisions and reduced driver maneuverability. Therefore, HOV lanes have been established on existing highways through widening projects, instead of converting existing lanes or shoulders to accommodate the special use of an HOV lane.

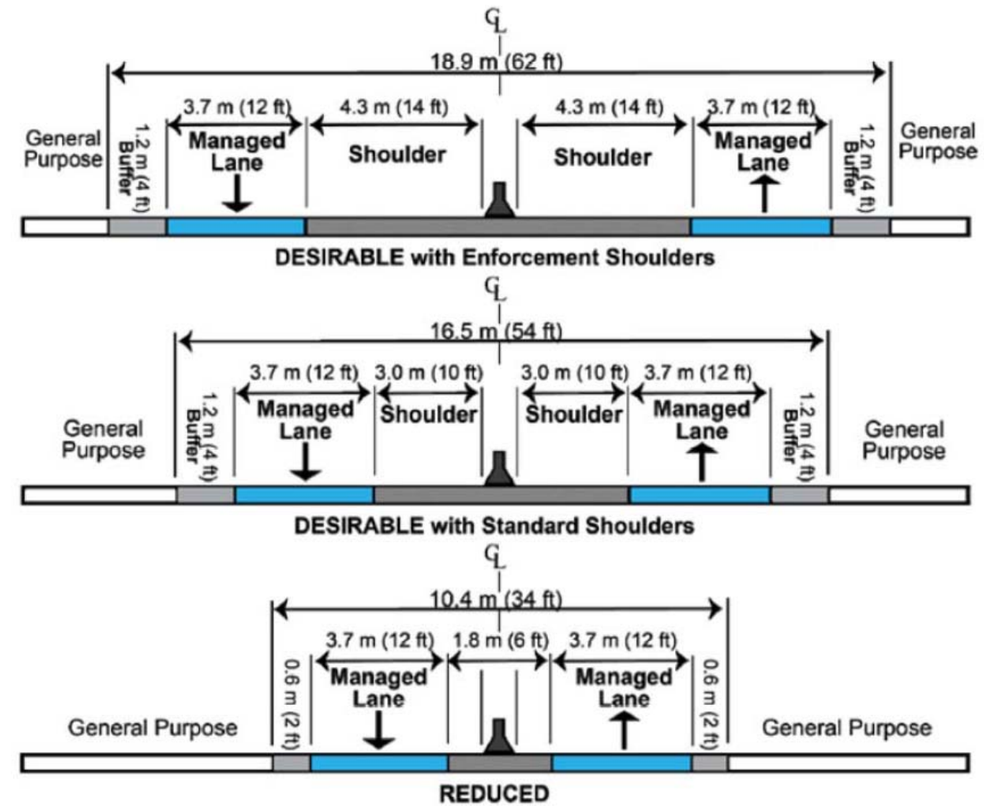
DESIGN OF TOLLED OR PRICED MANAGED LANES (2017)

[*Priced Managed Lane Guide*, Chapter 6. Design, Tolling and Pricing Program, Federal Highway Administration at https://ops.fhwa.dot.gov/publications/fhwahop13007/pmlg6_0.htm.]

The initial statement in this Guide is: "Design considerations for priced managed lanes will inevitably be driven by the corridors in which they are located." The upshot of this statement is that design will differ in accordance with characteristics of the highway corridor, available (and potential future) right-of-way, and previously adopted operational rules and requirements. A key aspect of managed lanes is that they represent a separated roadway system, and a safety analysis may be required to understand the ramifications of design requirements, operational needs, traffic volume levels, and access locations. This Guide identifies basic cross-sections for different configurations of managed lanes facilities, recognizing that adopting "desirable elements" may not work in every case. The Guide attempts to provide attributes of facility design that "bracket" potential desirable and "reduced elements" that may be required under constrained conditions. **Figure 1** depicts how this "bracketing" affects the facility cross-section.

With regard to access, the Guide recognizes this aspect of managed lanes as "a fundamental issue" associated with the design and operation of this type facility. Different levels of access control must be evaluated, especially trade-offs associated with cost, operational goals, safety, and enforcement. The Guide identifies three forms of access to managed lanes: continuous (e.g., current approach of HOV lanes in Phoenix metropolitan area); restricted (or limited), at-grade access; and grade-separated access, such as the Direct HOV (DHOV) connecting ramps being proposed for the Spine Corridor. The Guide also notes that there has been recent interest in providing continuous access to priced managed lanes, but this has implications for the number of tolling points, electronic toll collection (ETC) network, and enforcement. At-grade

Figure 4 | Alternative Managed Lane Cross-Sections for a Dual-Lane, Concurrent-Flow Facility



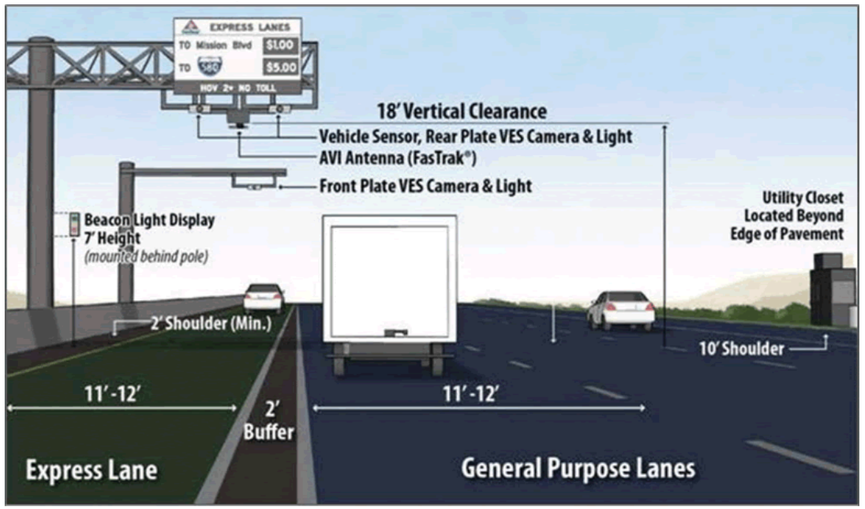
access, continuous and restricted, must consider existing and planned roadway geometrics and expected volumes associated with both the managed lane facility and GP freeway lanes.

> *In all cases, openings should be located and designed in a way that will not produce adverse impacts to the managed lanes and the parallel highway lanes. The locations of at-grade access openings need to be closely coordinated with highway entrance and exit ramps and allow adequate room for motorists to complete weaving movements when moving between the general-purpose and managed lanes and an entrance or exit ramp.*

The Guide addresses the various separation treatments available to control access; controlling access and separation are, in fact, the dominant considerations relating to managed lanes. Three forms or type of separation are distinguished: concrete barrier, pylons (or flexible posts), and striped buffers. All permit at-grade access. Modern tolling capabilities have allowed some communities to permit open access to priced managed lanes, meaning the separation does not require the fixed concrete barrier to enforce use of the lane(s). The ETC systems allow traffic to flow without stopping at a toll booth, and some facilities incorporate photo-enforcement systems to reduce the chance of missed vehicles. While it is relatively easy to understand how these systems would work in the closed environment of a limited-access managed lanes facility, it is less easy to understand how dynamic tolling occurs with a continuous-access facility. Nevertheless, as complicated as it may seem, the systems can identify vehicles, process toll transactions, identify and photograph license plates of potential violators, and inform enforcement personnel as

to account status through strategically placed beacons. An example of a managed lane toll zone design in provided in **Figure 2**.

Figure 5 | Typical Design of a Continuous-Access, Managed-Lane Toll Zone



Source: *Figure 6-18, Typical Managed Lane Toll Zone Design*, Parsons Brinckerhoff, extracted from *Priced Managed Lane Guide*, Chapter 6. Design, Tolling and Pricing Program, Federal Highway Administration at https://ops.fhwa.dot.gov/publications/fhwahop13007/pmlg6_0.htm.]

METHODS FOR CONTROLLING HOV LANES (2017)

[*Boston I-93 HOV Lane, A 10-Year "Temporary" Solution for Congestion Management Turns 20*, Road Zipper, Lindsay Transportation Solutions; and Road Zipper In The News, Lindsay Corporation at *http://www.barriersystemsinc.com/in-the-news-1* retrieved 3/14/2017]

As early as the 1970s, Boston began experimenting with design of and access to general-purpose (GP) freeway lanes converted to high-occupancy vehicle (HOV) lanes. Two early attempts were rejected, due to safety and political issues. In need of relieve of severe congestion on I-93 (Southeast Expressway) in the early 1990s, the Massachusetts Department of Transportation (MassDOT) adopted an interim (10-year) solution: a moveable barrier system. More than 25 years later, the interim solution has become a permanent solution. A movable barrier system, termed the Road Zipper, has proven to provide safety between opposing traffic flows and has been demonstrated to be the best alternative. MassDOT recently opted to reinvest in the Road Zipper rather than spend hundreds of millions, even billions, of dollars on a freeway widening project. This same system is operating, among other locations, in San Diego, CA, San Francisco, CA, Indianapolis, IN, Philadelphia, PA, Leicester, GB, Auckland, NZ, as well as Austria and Japan.

GUIDANCE ON HIGH OCCUPANCY VEHICLES (HOV) LANES (2016)

[Chapter V. Strategies to Reduce Congestion and Improve Air Quality, Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) Lanes, Freeway Management Program, Federal Highway Administration, September 2016, at *https://ops.fhwa.dot.gov/freewaymgmt/hovguidance/chapter5.htm*.]

This publication of the FHWA asserts "congestion pricing dampens demand for roads during peak hours and spreads usage over a longer time period. Differentiating the price of a good by the time of day effectively allocates limited capacity during periods of higher demand." HOV and high-occupancy toll (HOT) lanes are a cost-effective investment that can reduce congestion, but, also, "positively influence the mobility, safety and productivity of multimodal facilities, corridors, and metropolitan transportation systems." This publication makes a case for converting HOV lanes to HOT lanes, allowing motorists to opt for increased trip reliability for a price, i.e., payment of a toll. Because roadway capacity essential is being offered as a commodity for purchase, the quality of travel in the HOT lane must be monitored to assure speed is maintain and congestion within the facility is controlled.

The theory or philosophy of HOT lanes is that these facilities allow transportation officials to optimize vehicle throughput, drawing off some of the traffic in the GP freeway lanes, specifically single-occupancy vehicles (SOVs) that would otherwise be operating in the congested lanes. So, HOVs are no worse off in an HOV/HOT facility, and ineligible vehicles not meeting the minimum vehicle occupancy requirement, are better off paying to use the HOT lane. At the same time, vehicles operating in the GP freeway lanes also are better off, as some traffic has been diverted to the HOV/HOT facility.

This FHWA Guidance encourages development and use of HOV/HOT lane facility provided the performance of the HOV lane continues to meet specified performance standards. Conversion of HOV lanes to HOV/HOT lanes is encouraged where there is underutilization HOV lanes and the GP freeway lanes are experiencing congestion. Operation of a HOT lane requires, by Federal statute – "automatic tolling; dynamic tolls that vary with the level of congestion (i.e., responsive to real-time traffic conditions); adequate enforcement; and ongoing performance monitoring, evaluation, reporting, and modification of operations, when approaching degraded conditions." Changing HOT lanes pricing and vehicle occupancy requirement for HOV lanes is expected to assure facility performance should travel conditions degrade.

KEY POINTS REGARDING HOV LANES (2017)

[*Summary of Key Points RE: HOV lns*, "Frequently Asked HOV Questions at FHWA Freeway Management Program Web site, https://ops.fhwa.dot.gov/freewaymgmt/faq.htm, retrieved 2017]

Regarding the safety record of HOV lanes – "Studies have shown that HOV lanes are frequently as safe as, and in many cases safer than, unrestricted freeway lanes. The safest HOV lanes are those that are physically separated from the adjacent lanes with a concrete barrier, but that would be the case for general purpose lanes too."

SAFETY AND MANAGED LANES CROSS-SECTIONS (2016)

[*Safety Implications of Managed Lane Cross Sectional Elements*, Battelle and Texas A&M Transportation Institute for USDOT, FHWA-HOP-16-076, December 2016]

This study investigates how crashes are related to the dimensions of buffer-separated, managed-lane facilities. It leads off with a dual premise derived from previous studies that (1) reduced widths (lane and shoulder) are associated with more crashes, and (2) wider facilities envelopes result in fewer freeway crashes in terms of severity of the crash and severity of resulting fatalities and injuries. The analysis only investigated separated, single-lane, managed-lane facilities that did not require weaving maneuvers for ingress or egress and were operational 24 hours per day, seven days a week.

The data employed for this investigation included 128.0 miles of highway in California with flush buffers (no physical object, such as pylons) and 60.4 miles in Texas with 18.7 miles having flush buffers and 40.7 miles having pylon buffers. California data was for years 2007 through 2011 and Texas crash data was for years 2009 to 2014. The conclusions drawn from this study are:

- Wider facility envelopes are associated with reduce crashes on freeways at all severity levels and all fatal and injury severity levels –
  - Texas – wider envelopes result in 2.8 percent fewer total freeway crashes (all severities) for each additional foot of envelope width;

California – wider envelopes result in 2.0 percent fewer total freeway crashes (all severities) for each additional foot of envelope width; and
California – wider envelopes result in 4.4 percent fewer managed lane-related crashes (fatal and injury severity levels) for each additional foot of envelope width.
The width of the left (inside) shoulder of the HOV facility was significant for all severity levels, meaning greater safety benefit is derived from greater width of the shoulder.

Other factors were demonstrated to be significant in explaining the occurrence of managed lane-related crashes:
Decrease in crashes in the managed-lane facility with increasing volume in the GP lanes;
Increase with increasing volume in the managed lane;
Decrease with increasing managed lane width;
Decrease with increasing buffer width; and
Increase with increasing number of entrance ramps or access points.

The overall assessment resulted in the conclusion that lane width is the most influential predictor of safety, i.e., crash occurrence, followed by the width of the buffer. Findings and conclusions are summed thusly:

Results from several previous research studies have demonstrated that reductions in freeway lane width or shoulder width are associated with more crashes. Safety prediction equations are available to evaluate the tradeoffs.
Results from this study, along with other studies, also found that reductions in managed lane envelope widths (shoulder, lane, and buffer width) are associated with more crashes.
This study also found that narrow buffer widths (defined as being equal to and less than 3 ft) appear to be associated with more crashes as compared to 4-ft to 6-ft buffers.

Crash Prediction Methodology (2015)

[*Crash Prediction Method for Freeway Facilities with High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lanes*, Final Report, FDOT, Contract BDV32-977-04, August 2015]

This study focused on developing a crash prediction methodology to support evaluation of HOV or HOT lane projects on urban freeway segments. Specifically, safety performance analyses primarily emphasized potential impacts associated with different types of separation between managed lanes and GP lanes. Modeling methods for HOV lanes relied on five years of data available from California, Washington, and Florida, and estimates were developed for the occurrence of fatal and injury (FI) crashes and all crashes. All of the HOV facilities include one HOV lane in each direction.

The model development activity also focused on freeways with HOT lanes, relying on data available for a four-year period. The HOT lane facilities modeling exercise included 48 segment on 27 miles of freeways, also in California, Washington, and Florida. All facilities investigated include two HOT lanes in each direction. Interestingly, safety performance revealed though this effort indicates spatial separation is a key factor with respect to the occurrence of crashes. "Facilities with a 1-foot separation are estimated to have more crashes than those that have a 3-foot separation which in turn have more crashes than facilities with a 20-foot separation" (all other things being equal).

"The effect of separation type on crash rates [was] found to be statistically significant only in the models for ten-lane facilities." The FDOT team developed separate equations to reflect six-, eight-, ten-, and twelve-lane facilities. The modeling effort was undertaken, in part, due to the lack of a methodology for predicting crashes and safety benefits associated with freeway facilities with managed lanes. The focus of the models is the type of separation between managed lanes and GP freeway lanes. FDOT presents models to estimate fatal and injury (FI) crashes and all crashes, including injury severity levels of 'K', 'A', 'B', and 'C'. The "All Crashes" category includes the FI crashes and property damage only. The models are developed in a spreadsheet platform.

Findings Relative to Freeway with HOV Lanes:

Crashes on freeways with HOV lanes increase with increase in traffic volume (AADT) and segment length (measured in miles).
Overall, separation type impacts the number of crashes on ten-lane facilities.
Using a buffer instead of a painted stripe will lead to fewer total crashes on 10-lane freeways; however, increasing the width of the buffer will not reduce total crashes.
A wider buffer (2-3 feet) leads to fewer fatal and injury crashes.
Differences in separation type are not statistically significant in the case of six, eight, and twelve-lane facilities.
Increasing the width of the left shoulder (measured in feet) results in a decrease in the number of crashes for all cross-sections modeled, except the twelve-lane facility.

Findings Relative to Freeway with HOT Lanes:

As noted above, model estimates indicate a 1-foot separation will have more crashes than a 3-foot separation and an especially wide 20-foot separation (the Dallas, TX, facility has both a left shoulder for the general purpose freeway lanes and a right shoulder for the HOT lanes).
Not surprisingly, the occurrence of crashes increases with increases in traffic volume, measured as average annual daily traffic (AADT).

Safety As A Planning Criterion (2015)

[High-Occupancy Vehicle Facilities, Chapter 1410, WSDOT Design Manual, Nov 2015]

Safe, efficient, and enforceable operations are considered one of six planning elements for evaluating appropriate design options for a HOV facility. The Manual recognizes that a separated facility, although the most expensive option, is "normally" more efficient and provides a higher level of safety compared to non-separated facilities.

Managed Lane Separation Treatments (2012)

["Managed Lane Separation Treatment," *Managed Lanes Network Development Strategy – Phase I*, Maricopa Association of Governments, February 2012]

This White Paper looks at three approaches for separating managed lanes from adjacent GP lanes:

Painted line and painted buffer barrier;
Traffic channelizer with physical (flexible post or pylon) or painted barrier; and
Physical barrier.

The assumption for each is "restricted access," meaning the highest level of separation – physical barrier – is the standard for evaluating performance.

The painted line or buffer separation treatments support continuous access (ingress and egress) along the length of the HOV facility. Current guidance in the Manual on Uniform Traffic Control Devices (MUTCD) recognizes "concurrent" operations of an HOV facility without unlimited continuous access. Solid white lines (single or double) are intended to discouraged access movements, and broken or dashed white lines (single or double) are intended to identify locations where access is permitted. This MUTCD guidance is aimed at minimizing the frequency and randomness of access movements to reduce opportunities for conflicts between the HOV facility traffic and traffic operating in the GP freeway lanes.

The channelizer treatment involves installation of brightly colored, 42-inch tall, reflective posts aligned to guide traffic into and out of the HOV facility and establish a more visible barrier between the HOV facility and GP freeway lanes. Channelizers typically are flexible and permanently affixed to the pavement at 12-foot intervals as well as centered within a striped buffer zone. Channelizers are more permanent than pylons, which can be sent flying, if a motorist

opts to exit or enter the HOV facility where the pylons are present. Even so, inadvertent vehicular impacts can damage the post-type channelizers, requiring, according to the White Paper, "roughly 1/3" to be replaced annually.

The White Paper states physical barrier separation is preferred when opposing traffic flows could create direct conflicts. A physical barrier also may be appropriate in concurrent flow cases, where the objective is to maximize the speed differential between the HOV facility and the adjacent GP freeway lanes. Vehicle operators desiring to use the HOV facility are permitted to enter and exit only at certain points; therefore, traffic operating within the HOV facility effectively is contained or restricted within the barrier. Accordingly, there is a need within the HOV facility for a shoulder (typically 10 feet wide) to accommodate emergency breakdowns and permit maneuvering, if necessary, to avoid other vehicles. These requirements impose greater requirements for right-of-way. A dual-lane HOV facility, in effect, offers the second lane as an emergency area, if necessary, which can make the widths and right-of-way requirements of the single-lane with shoulder and dual-lane facilities similar.

The White Paper address four issues determined to influence the lane separation decision: Safety, Traffic and HOT Lane Operations, Enforcement, and Emergency Access. Significantly, the White Paper, prepared as recently as 2012, notes the "no national study has been undertaken, and no database exists, from which specific causal factors associated with separation treatments could be isolated." Some local studies have been conducted and some observations can be noted relative to restricted access studies in California and Texas. The White Paper presents the following observations:

- Safety
  - Assuming all other factors to be equal (e.g., mix and density of traffic, roadway geometrics, access locations, etc.), barrier separation is safer than non-separated treatments.
  - There tends to be a greater number of crashes at entrance locations to concurrent, barrier-separated HOV facilities, where barrier attenuators (i.e., crash cushions) are installed.
  - Channelizers present a readily visible barrier and help reduce the occurrence of deliberate buffer crossing, but do not mitigate the potential impacts of crashes within the HOV facility or crashes that cross over the flexible barrier with from or into the HOV facility.
  - Buffer-separated HOV facilities aid in reducing crashes, if the buffer area is sufficiently wide (4-foot preferred) to allow diversionary vehicle movements, but not wide enough to be perceived as a place of refuge for stalled or disable vehicles.
  - The safety associated with all treatments, in terms of both crash occurrence and severity, is influenced by the length and location of access locations and the speed and density of traffic streams. The White Paper notes that crash data from Dallas experience indicates a higher crash rate and greater severity per incident is associated with the speed differential between the HOV facility and GP freeway lanes and difficulty of entering and exiting the HOV facility.
  - A single-lane HOV facility lacking an inside shoulder limits opportunities for diversionary actions by motorists in the lane and increases the risks of crash occurrence.
  - The use of channelizers, which have a greater requirements for continual maintenance relative to painted lines, painted buffers, and physical barriers, compounds safety issues associated with traffic streams with the presence of maintenance personnel and equipment.
- Traffic and HOT Lane Operations
  - Operational and safety issues associated with ingress/egress locations and tolling sites of HOT Lanes are similar to HOV lanes.
  - The White Paper suggests that "…barrier treatments offer motorists greater confidence that an incident in adjacent lanes [HOV/HOT or GP freeway lanes) will not affect them."
- Enforcement
  - Painted and buffer-delimited managed lanes typically have greater violations of operational criteria than barrier-separated HOV or HOT facilities.
  - Painted and buffer-delimited managed lanes generally are more difficult to enforce, as motorists can more easily move from the dedicated facility and the GP freeway lanes.
  - Automated tolling with transponders and pay-by-mail methods replace physical roadway enforcement with other administrative enforcement methods, reducing exposure of both motorists and enforcement personnel to traffic streams.
- Emergency Access
  - Barrier-separated HOV/HOT managed-lane facilities increase the difficulty of providing quick response to and clearing of travel disruptions, which can be mitigated by the presence of a wide shoulder or a second travel lane.
  - Concurrent, painted and buffer-delimited facilities allow emergency vehicles to access affected lane(s) of a HOV/HOT managed-lane facility, even crossing channelizers, if necessary.
  - Critical questions to be addressed regarding emergency access are: expected frequency of incidents; desired response time; availability of access to the affected lane(s); presence of bypass shoulder or lanes for use by emergency vehicles; and costs associate with providing policy-level access relative to the safety of motorists and emergency personnel.

The White Paper concludes that available information indicates very few concurrent flow HOV/HOT managed-lane facilities are barrier-separated. It notes the degree of safety varies among the separation treatments investigated, and no national study nor does any database exist to provide specific causal factors by treatment. Only generalized inferences may be drawn from available information and published literature. However, a consensus exists that, all things being equal, barrier separation is safer than non-barrier treatments, specifically painted and buffer-delimited treatments. But, the White Paper is quick to point out that both treatments "…are safe, approved, time tested methods of separation for concurrent flow lane applications by FHWA and all of the Departments of Transportation across the United States."

California's Managed Lane Design Policy (2012)

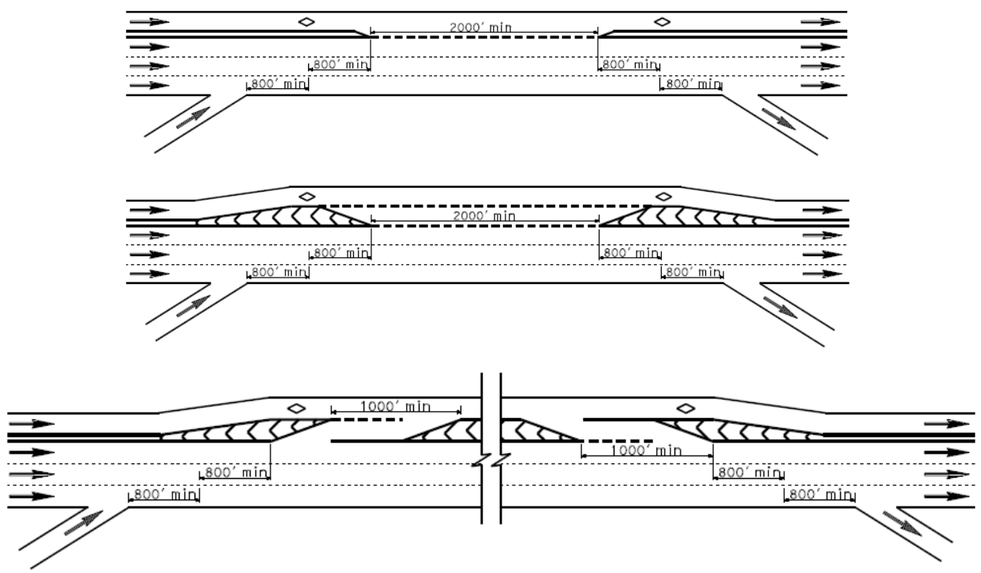
[*California's Managed Lane Design Policy*, Joe Rouse, Caltrans Division of Traffic Operations, Office of System Management Operations; PPT Presentation, July 2010]

This presentation by a Caltrans official discusses a policy directive to guide "Intermediate Access" design of the State's HOV network and conduct of operational analyses. He identifies three types of Intermediate Access:

- Weave Zone – Combined ingress/egress [with no weaving lane]
- Weave Zone – Combined ingress/egress with a weaving lane
- Merge Lane – An ingress or an egress location with a merging lane.

Three cross-sections were presented for each of these conditions, as shown in **Figure 3**. It was noted that operating performance of Intermediate Access "openings" should be level of service (LOS) 'C' or 'D', and should not be co-located with an area of recurrent congestion (existing or expected). Design guidelines for Intermediate Access locations were established at "800 feet per lane change between opening and adjacent ramp" and openings should be 2,000 feet in length. Lighting would be necessary at all Intermediate Access locations and recommended for areas where major weaving would take place.

Figure 6 | California Managed Lane Access Design Policy Cross-Sections



The new policy will be applied to all managed-lane projects during the environmental phase. Analyses will focus on assuring the revised facility configuration will meet operational thresholds and include evaluation of: freeway mainline flow, merge/diverge analysis of drop ramps/direct connectors, and assessment of ingress/egress at access locations. Safety analyses will be performed to ensure design and operation of HOV/HOT managed lane facilities does not create new safety "hot spots" or increase the potential for crashes, particularly crashes resulting in severe or serious injuries. The design under discussion would permit direct ingress/egress at access locations and would supplant the use of solid yellow lines with solid white lines.

FEDERAL HOV GUIDANCE (2012)

[Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) Lanes, Freeway Management Program, FHWA, November 2012, at https://ops.fhwa.dot.gov/freewaymgmt/hovguidance/]

This document presents guidance that applies to all federally-funded, HOV facilities, superseding previous versions issued in August, 2008. The document provides information to aid States in the planning, design, operation, and management of HOV and HOT facilities. The Guidance is non-binding and provides examples for States to follow in the process of defining and evaluating proposed changes to HOV lane operations, including proposals to convert an existing HOV lane to a HOT lane. The Guidance specifically states:

> *In locations where existing or anticipated excess HOV lane capacity is available, conversion to a HOT lane facility is encouraged as a way to increase throughput and to provide additional travel options for drivers. As part of an overall approach to respond to increased travel demand and address traffic congestion, HOV and HOT lanes can be a practical alternative to adding more general-purpose travel lanes. The FHWA encourages the implementation of HOV or HOT lanes as an important part of an area-wide approach to help metropolitan areas address their requirements for improved mobility, safety, and productivity, while also being sensitive to environmental and quality of life issues.*

MANAGED LANES HANDBOOK

[8.0 Managed Lanes, Updated Chapter – Managed Lanes Chapter for the Freeway Management and Operations Handbook, Federal Highway Administration, January 2011, at https://ops.fhwa.dot.gov/freewaymgmt/publications/frwy_mgmt_handbook/toc.htm]

This FHWA publication states that one commonality among all managed lane facilities is "…active demand and system management." This chapter of the Handbook focuses on the latest practices, strategies, and technologies associated with the implementation and operation of managed lane facilities. Six primary goals are identified for implementing managed lanes: improve traffic operations, facilitate movement of people and goods, enhance performance and efficiency, promote air quality goals, improve safety, and address return on investment. The reason for implementing managed lanes is "…to preserve a reliable trip that is viewed as a preferable alternative over congestion that exists in the general purpose lanes."

Implementation, however, should be intended as a complement to a comprehensive congestion management program that may include, but not be limited to: "…ramp metering, incident management, traffic demand management (TDM) such as rideshare promotion, and associated programs that are both complementary and synergistic to overall regional mobility goals." The Handbook points out that, although managed lanes may be moving more people, the public perception of the lanes may be that there is active capacity that should be used. This phenomenon requires ongoing education and outreach to inform the public of the utility of managed lanes, which can be support by performance monitoring.

Grade-Separated, Direct HOV (DHOV) Access at Maryland Avenue on Loop 101 (Agua Fria Freeway)

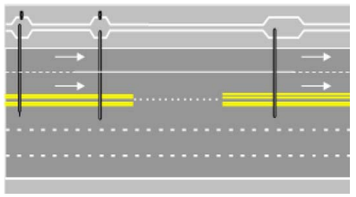
Regarding access, the Handbook notes that limitations on access to managed lanes establishes an operating environment with minimal disruptive impacts facility. It associated with vehicles entering and exiting the also is noted that the facilities reduce side friction multiple associated with concurrent travel of vehicles in or both) lanes. Typically, barrier-separated facilities (HOV, HOT, are accessed via grade-separated ramps referred to as Median Drop Ramps or Direct HOV (DHOV) Ramps. These access treatments generally connect with park-and-ride (P&R) lots, transit centers, and crossing arterial streets. This adds to the safety and expediency of travel associated with the managed lanes and aids in developing a regionally connected system of managed lanes.

The Handbook presents a section specifically addressing access treatments, specifically noting that access treatments "…impact the operation characteristics of a managed lane facility." Most access on restricted (i.e., limited access), concurrent lanes is spaced less frequently than access provided for the GP freeway lanes via on- and off-ramps, and the most common access treatment is at-grade at designated locations or an opening along an inside lane. The Handbook points out that "access spacing of two to three miles is common for most restricted access treatments." It describes five types of access treatments:

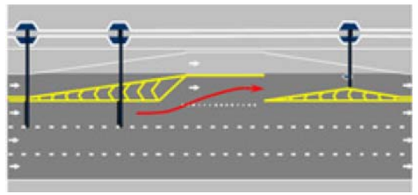
- **Open** – Open or continuous access is the most common treatment, which allows entry into and exit from the managed lane practically anywhere along its length; this treatment is not an effective access protocol for segment-based tolling.
- **Zones** – Access zones (or weave/merge zones) are associated with a large number of concurrent-flow facilities. This treatment establishes specific zones, using signage and pavement markings, to regulate entry into and exit from the facility. Zones must be at least 1,000 feet in length – preferably 2,000 feet – with a minimum of 600 to 800 feet between entry/exit and the on- and off-ramps providing access to the GP freeway lanes to

facilitate weaving/merging. This type of treatment creates a zone of simultaneous ingress and egress movements similar to continuous-access, concurrent managed lanes (e.g., Phoenix metropolitan area HOV lanes), but only at certain predetermined locations.

Designated Access Zone for Ingress and Egress



Designated Ingress Zone with Slip Ramp to Managed Lane



Source: Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) Lanes, Freeway Management Program, FHWA, November 2012, at https://ops.fhwa.dot.gov/freewaymgmt/hovguidance/

Slip Ramps – At-grade ramps provide access to the managed lanes when separated from the GP freeway lanes by a barrier, physical structure or painted buffer. The ramps facilitate one-way ingress and egress and reduce friction associated with weave/merge movements directly impacting the left-most GP freeway lane.

Median Drop Ramps – Otherwise reference as DHOV ramps, these establish discrete points of ingress and egress (see DHOV discussion above).

Direct Freeway-to-Freeway Connection – This access treatment is warranted when there is a high volume of traffic anticipated between one facility and another. It is not immediately relevant to the access issues associated with the proposed dual managed lanes in the Spine Corridor.

Determining the best operational scenario for managed lanes requires an assessment of a number of factors. Information in the Handbook indicates the continuous entry/exit HOV lanes, such as are established in the Spine Corridor, are appropriate, as they serve GP freeway traffic. The Handbook points out that, historically, "…about 60 percent of HOV lane-miles in the US have been unrestricted or open access, and the other 40 percent have restricted access to designated weave zones largely through pavement markings." Both types of access can be safe and function well, according to various studies. Transportation officials in southern California are moving toward lifting access restrictions on some managed lanes. Open access is being justified on the benefits of allowing greater flexibility in use of the managed lanes and essentially spreading weaves and merges along the path of the facilities rather than focusing such movements at ingress and egress locations. On the other hand, the addition of tolling of other HOV lanes "…is creating the need to restrict access between toll zones." Tolling is more problematic and complex, if access is not controlled and limited to certain locations. Access restrictions are justified by the desire or need to: control ingress and egress at designated locations; reduce unnecessary or provide better direction to weaving and merging; discouraging short-distance trips from using the lanes; and limiting violations by queue jumpers.

Effective enforcement actions and operating policies are necessary to assure adherence to access, eligibility, and pricing restrictions of managed lanes. Tolling is considered a form of enforcement, but it also allows for the control of volume of travel through the corridor and, therefore, aids transportation officials in optimizing corridor operations. With regard to HOV lane operations, no technology exists that can definitively determine and communicate in real-time the number of occupants in a vehicle that is accepted by police organizations or the courts. Concurrent-flow, continuous HOV facilities are particularly difficult to enforce, because motorists can freely enter and exit at any point to avoid detection. Barrier-separated facilities present more of a deterrent to violators, as they must be willing to travel longer distances in violation of established restrictions. Enforcement activities can be strategically positioned just inside the ingress point or immediately outside the egress point. Ultimately, various strategies to address enforcement roles need to be evaluated to account for the respective business rules, police agency preferences, and facility design that can accommodate the requirements for enforcement.

Current Industry Trends for Separating Express Lanes from General Purpose Lanes

[White Paper, Current Industry Trends for Separating Express Lanes from General Purpose Lanes, AtkinsGlobal.com, September 2011]

This White Paper was prepared to address the advantages, disadvantages, and impacts of lane separation techniques relative to managed lanes. It highlights six key factors to consider when selecting the type of separation to be deployed.

Safety – The White Paper points out that studies show the barrier-separated systems are the safest. Nevertheless, this separation technique presents a concern relating to incident response, due to limited access points. Also, fixed barriers are viewed as potential unforgiving at contact, and designs may not give motorists adequate time to correct or modify an operating error.

Right-of-Way – Space requirements typically are greater where access points to/from are established. Design at access points needs to carefully consider the weave and merge requirements of ingress/egress actions between the express lanes and GP freeway lanes. Constrained rights-of-way may require certain or site-specific types of separation requiring design modifications of the adopted cross-section and waiver of standards.

Cost – Permanent barriers are the most expensive type of separation; pavement markings are the least expensive. However, pavement markings and post/pylons, when adopted as separation techniques, have greater maintenance/replacement requirements that adds to long-term costs. Flexible/tubular delineators, such as post/pylons, require the greatest amount of attention/maintenance tend and represent a greater hazard to traffic, as they can be dislodged by errant vehicles.

Roadway Design Characteristics – Four potential design schemes are identified: reversible lanes, lanes operated to accommodate peak direction traffic always requiring barriers; concurrent flow, lanes operated in the same direction as GP freeway lanes, most common; elevated, lanes are grade-separated eliminating potential conflicts except at access points; and mixed mode, lanes operated as HOV or tolled (HOT) that are open to GP traffic on off-peak hours. The latter HOV/HOT mixed mode scenario is no very common and is viewed at potentially confusing for motorists.

Operational Characteristics – Four potential operational scenarios are identified that impose restrictions or requirements to control traffic: vehicle occupancy, which requires physical/visual enforcement and may affect the type of separation deployed; vehicle type, which affects the ultimate footprint of the facility; dynamic price tolling, which requires constant monitoring to control volume of traffic and can easily be violated without proper separation; and time-of-day tolling, which controls access by time of entry, but lacks control on traffic volume associated with dynamic price tolling.

Access Points - The selected separation technique must consider type of access and the number of access points, i.e., multiple access points, minimal access points, or direct access at crossroads to/from the GP freeway lanes. Access directly affects interaction between vehicles using the managed lanes and vehicles operating in the GP freeway lanes, specifically weaving and merging dynamic. The type of access also affects the design and geometrics of the facility; barriers require crash attenuators at ingress ends, but flexible delineators (e.g., post and pylons) and pavement markings are more forgiving.

EMERGING ISSUES: BARRIER VERSUS BUFFER SEPARATED MANAGED LANES (2010)

[Technical Memorandum 17B: Advantages and Disadvantages of Barrier versus Buffer Separated Managed Lanes, Atlanta Regional Managed Lane System Plan, Georgia Department of Transportation, January 2010]

This White Paper explored the advantages and disadvantages separating managed lanes from GP freeway lanes by means of a barrier or buffer system. Factors identified as contributing to the selection of a barrier or buffer system included: design, cost, access, safety, tolling/congestion pricing operations, enforcement, and public perception. The advantages and disadvantages are discussed in the White Paper, and a two decision matrices prepared addressing: public perceptions of pavement markings used for buffer-separated facilities, concrete barrier, pylons, and grade separation; and the factors noted above relative to buffer-separated facilities and barrier-separated facilities. Some key points made in this White Paper relative to safety, access, and enforcement are excerpted below:

Safety –

- **Buffer System** – The buffer-managed lanes system is either found less safe, due to the potential accidents caused by concurrent speed variations, or equally safe as barrier systems. Accident hot spots along managed lanes corridors are generally a result of congestion and not specifically the design or operation of the facility itself.
- **Barrier-Separated** – A benefit for barrier separated systems is that accidents in the GP freeway lanes do not generally affect operations or safety within their isolated system. Buffer systems, on the other hand, are directly impacted by accidents [and speed variations] in the GP freeway lanes, often reducing flow to a rate similar to the directly affected lanes.

Access –

- **Buffer System** - Both barrier and buffer systems vary in their ability to provide access for travelers. Buffers can be designed with continual access or with painted ingress and egress locations. Buffers with continual access can have the undesirable consequence of reducing capacity in the managed lanes, due to friction between the quick moving managed lane and the slower moving GP freeway lanes. The continued near proximity between the quick and slow moving lanes continues to provide concern for travelers as there is no physical means to prevent a motorist from merging into the managed lanes facility unexpectedly.
- **Barrier-Separated** – The problem of speed differential turbidity is generally alleviated in barrier separated managed lanes systems, where travelers are isolated by a physical barrier preventing access in most locations from the general purpose lanes. Barrier managed lanes trips are targeted more strongly to individuals making longer excursions with foresight into where they will be entering and where they will be exiting the system. In barrier-separated systems, access is best provided by direct ramps and transit centers, keeping the system in less direct interaction with the general purpose lanes, and minimizing multi-lane merging for ingress and egress.

Enforcement –

- **Buffer System** – Buffer-separated managed lanes facilities are harder to enforce and are easier for single occupancy vehicles to abuse. The ease with which travelers can ingress and egress the buffer-separated managed lanes system make it more difficult for law enforcement officials to closely monitor and enforce regulations. Moreover, this phenomenon reduces the incentive to carpool and leads to additional congestion on the general purpose lanes of the highway as a result.
- **Barrier-Separated** – Barrier-separated systems are more difficult to ingress and egress and are, therefore, found to have high levels of compliance. Travelers wishing to cheat the system have to willingly commit to riding a substantially longer distance illegally than in a buffer-separated system. As a result, public confidence in the functionality of barrier-separated systems remains generally high.

HOV TO HOT LANE CONVERSION (2009)

[Technical Memorandum, Final, I-77 Feasibility Study (I-85 to Griffith Street), Task Order No. 1 – I-77 Widening & HOV Facility Extension Sub-task 1.B, Performance Measures Task Order No. 2 – I-77 HOV/HOT Conversion Sub-task 2.B, Performance Measures, TIP Project No. FS-0810B, North Carolina Department of Transportation, June 2009]

This project was undertaken by the North Carolina Department of Transportation (NCDOT) specifically to investigate the feasibility of and ultimately convert standard HOV lanes (i.e., carpool lanes) serving each direction on I-77 to two express, or HOT, lanes in each direction. Information about the project at the I-77 Project Web site (www.i77express.com) notes that NCDOT is following the lead of transportation agencies in California, Colorado, Texas, Virginia, Florida and Georgia by investing in express lanes to alleviate traffic congestion. The express lanes are viewed as being successful at making travel more efficient for all drivers in urban areas. The project plan calls for entry and exit points at several locations along the 26-mile, I-77 project corridor (**Figure 4**). These points will give drivers multiple opportunities to decide whether they want to take advantage of the time-saving benefits the express lanes offer at the specified cost. Ingress/egress flexibility will be facilitated by the fact that each segment in the corridor will be tolled separately. Drivers will see signs prior to the entry point of each segment that indicate the amount of the toll. Under Questions and Answers relating to the project, the sponsors indicate merge lanes are designed with safety in mind, providing plenty of room for drivers to enter and exit the express lanes using at least six designated points. No specific safety information has been made available.

REGIONAL REVIEW OF HOV LANES FOR DALLAS-FORT WORTH METROPLEX (2009)

[*HOV Lanes: DFW Regional Review*, Executive Summary, The Metropolitan Transportation Plan – Priced Facilities, Aug 2009]

This review was undertaken following several years of HOV lane operations in the Dallas-Fort Worth (DFW) Metroplex. The overview focuses on:

- Need for these facilities;
- History and changes to these facilities; and
- Answers to questions and concerns related to the design, management, and operation of the facilities.

One section of the White Paper is title "Safety of Design – HOV Facilities and Crash History." The White Paper notes there were 314 HOV facilities in the U.S. at the time. Almost one-half were established as "paint stripe" and buffer-separated facilities: 50 of the HOV lanes were concurrent-flow, buffer-separated, and 102 were concurrent-flow, separated by a paint stripe. Since opening in January, 2006 (a three-year period preceding this report), three fatalities were reported in association with the HOV facility on US-75 – a pylon and curb system – and five fatalities (four incidents) were reported in association with the I-635 HOV facility. A summary of these incidents by corridor is presented in the White Paper:

Figure 7 | I-77 Express Lanes Plan

US-75

Driver struck a pylon on the left, abruptly swerved right, crossing all freeway lanes prior to flipping and coming to rest in the left lane of the frontage road. Drive died at the scene.

Motorcyclist crossed the pylon barrier at an illegal location and was struck by a vehicle operating within the HOV lane. Motorcyclist died after being transported to the hospital.

Driver operating legally in the HOV lane made an improper exit through the barrier, resulting in a second car losing control and crashing. Passenger died after being transported to the hospital.

I-635

A vehicle, parked perpendicular to the HOV lane with passenger side facing downstream, was struck by a bus, causing the vehicle to spin into the concrete median barrier and ricochet into the left lane of the freeway. Passenger died after being transported to the hospital.

A vehicle in the left lane of freeway rear-ended another vehicle, which was thrown across the barrier into the HOV lane. A motorcyclist operating legally in the HOV lane, swerved into the freeway's left lane colliding with the vehicle that rear-ended the other vehicle. The motorcycle skidded across the entire width of the freeway, coming to rest in the median between the main lanes and the frontage road. The motorcyclist died after being transported to the hospital. The passenger in the rear-ended vehicle died at the scene.

A driver, attempting to change lanes from the left lane to the center lane, found the lane to his right occupied by another vehicle. The driver overreacted, abruptly steering back through the left and crossing into the HOV lane. A vehicle traveling legally in the HOV lane was struck, mounted the concrete median barrier, and rolled out into the left lane of the freeway, ultimately killing the driver.

A driver, wanting to get cell phone photos of an 18-wheeler on fire in the opposing lanes, parked on the shoulder, crossed the freeway on foot, and was struck by a vehicle operating legally in the HOV lane. Drug test results for the pedestrian struck in the HOV lane were positive for cannabis, PCP and depressants.

Following several years of operation subsequent to establishment of the US-75 and I-635 HOV lanes, a TxDOT-contracted review shows "…the crash rate in the first year of operation on I-35E increased 56% and on I-635 increased 41%: speed differential and subsequent access, either exiting or entering, between HOV lanes and GP freeway lanes was most pressing safety concern." The system in place at the time of this White Paper consisted of pylons with 13-foot spacing and limitations on ingress/egress locations. The locations of access points had been selected based on where speed differential concerns were not a critical issue. The evenly spaced pylons created a visible barrier that demanded driver attention, while supporting timely exit of the facility, if necessary, with assistance of freeway patrol officials.

TxDOT originally shied away from too many access locations, due to concerns for traffic operations and traffic conflicts. In the case of US-75, the Department favored terminating HOV lanes in areas where the speed differential was minimized, which excluded an ingress/egress location to serve the City of Richardson, TX. The White Paper notes that discussions were underway to evaluate adding a "wishbone direct ramp" in Richardson to accommodate the many motorists desiring to access the community and use the facility for commuting out of the community. The objective was seen as creating a three-pronged solution that would: satisfy travel demand associated with GP freeway lanes to serve regional mobility, allow local community access, and assure the HOV lanes serve commuter traffic that contributes to the goal of meeting regional air quality goals.

Facility Configurations and Safety (2009)

[*Safety Performance of High-Occupancy Vehicle (HOV) Facilities: Evaluation of HOV Lane Configurations in California*, Safe Transportation Research & Education Center, Kitae Jang, et al, January 2009]

Collision data associated with continuous- and limited-access HOV facilities were reviewed. A key difference between the two types of HOV facilities is that continuous-access lanes generally support special segregated travel opportunities only during peak periods (e.g., 5-9AM and 3-7PM), Monday-Friday. Limited-access HOV facilities, which often require a toll, are operated 24 hours per day, seven days per week. Thus, the comparison focused only on collision incidents occurring in the peak periods.

This study team concluded "…HOV facilities with limited access offer no safety advantages over those with a continuous access." The combined collision rate for limited-access facilities and adjacent GP freeway lanes was found to be higher than the combined collision rate of the continuous-access HOV lane and adjacent GP freeway lanes. However, it was noted that shoulders greater than 8 feet in width result in "…significantly lower collision rates, regardless of access type." The study team also found collision rates were "markedly higher" for a limited-access HOV facility with a combination of (1) short ingress/egress lengths and (2) close proximity to the nearest on/off ramps. Also, the study team determined that "…limited-access HOV facilities with a combination of short ingress/egress length and a close proximity to the nearest on- or off-ramp can result in markedly higher collision rates than other limited-access freeway segments…." It was noted that these factors needed more systematic investigation to determine the degree of effect.

Comparison of Limited v. Continuous HOV Facilities (2009)

[A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV) Facilities, Institute of Transportation Studies for Caltrans, CA09-0968, March 2009]

This report provides a comparative analysis of the safety performance of limited-access and continuous-access HOV facilities in California during peak travel periods between 1999 and 2003. Findings from the study indicate limited-access facilities offer "…no safety advantages over those with continuous access, whether measured by percentage of collisions, collisions per mile, collisions per VMT, or collision severity." The principal conclusion drawn from these findings is that "maintaining adequate shoulder and total [facility] width is essential…."

Study recommendations include emphasis on general design features that have the potential to maximize safety associated with the limited-access facilities, including: adequate total facility and shoulder width, adequate length of access (ingress and egress) sections of the facility, and establishing an adequate distance between access locations and freeway on/off ramps. These recommendations for design modifications are aimed at addressing two concerns: (1) issues of safety associated with lane-changing concentrated at ingress/egress locations; and (2) the relatively short distance within which lane-changing occurs proximate to freeway ramps and HOV ingress/egress locations.

A key issue associated with limited-access facilities is that ingress and egress maneuvers can be too proximate with freeway on/off ramps. Where this occurs, motorists must immediately weave across consecutive lanes to the facility entrance from a freeway entry point and/or exercise a similar activity to reach a desired freeway off-ramp subsequent to the exit point. Thus, the safety performance of the HOV/HOT managed-lane facility and adjacent free-flow lane of the freeway are likely to be impacted under the limited-access scenario. This study was able to investigate crashes patterns occurring between 1999 and 2003 for four limited-access and four continuous-access facilities.

The investigation revealed that limited-access facilities, when compared to the continuous-access facilities, had a higher percentage of total collisions across all freeway lanes and a higher number of: total collisions per mile per hour; fatal and injury collisions per mile per hour; total collisions per VMT; and fatal and injury collisions per VMT. The investigation found that shoulder width "…was a strong predictor of safety performance…" for both types of facilities, and the limited-access facilities exhibited "…a higher proportion of rear-end collisions…" compared to side-swipe collisions. This is a result that might be expected, given that generally there is only one lane of traffic in the limited-access facility eliminating the possibility of side-swipes.

Regarding the safety performance of the adjacent freeway lane relative to the limited-access and continuous-access facilities, the former exhibited: a higher percentage of total collisions across all freeway lanes; a higher number of: total collisions per mile per hour; a lower number of fatal and injury collisions per mile per hour; a higher number of total collisions per VMT; and a lower number of fatal and injury collisions per VMT. This aspect of the investigation found the freeway lanes adjacent limited-access facilities had lower levels of safety performance for total collisions than those adjacent continuous-access facilities. However, the limited-access facilities performed slightly better relative to fatal and injury collisions. This could indicate reduced severity of crashes, possibly due to slower speeds and greater awareness deriving from clearly defined ingress/egress locations, as opposed to random or uncontrolled ingress/egress associated with the continuous-access facilities.

The investigation also focused on collision records for the facilities and the adjoining lanes combined. The analysis revealed the limited-access facilities reflected the performance of the HOV/HOT manage-lane facilities alone, as cited above, resulting in a lower overall safety performance for the limited-access facilities. Thus, the study conclusion is that establishment of limited-access facilities would not be justified as a project to enhance safety. Still, the study provided the basis for defining three recommendations, i.e., design features, to mitigate the safety issues of limited-access facilities:

- Maintenance of adequate shoulder width is essential;
- Optimize the length of ingress/egress sections (collision rates were found to be higher in the short access sections);
- Optimize distances between ingress/egress locations and freeway on/off ramps – "…locating access areas in close proximity to on/off ramps should be avoided."

Safety of HOV Facilities in California (2008)

[Safety Evaluation of High-Occupancy Vehicle (HOV) Facilities in California, Intellimotion, Volume 14, No. 2, 2008, California Partners for Advanced Transit and Highways (PATH)]

This study focused on evaluation of collision patterns associated with continuous- and limited-access, concurrent-flow HOV lanes with specific attention to safety performance. It is a follow-on study to *A Comparative Safety Study of Limited versus Continuous Access High Occupancy Vehicle (HOV)*, and the study was designed to examine detailed geometric and traffic data, as available. The study focused on four geometric factors: shoulder width, total width (shoulder + HOV lane + buffer), spatial collision patterns, and ingress/egress analysis.

The principal findings of this research "…show that the HOV facility with limited access offers no safety advantages over the one with a continuous access." Nevertheless, the study also notes "the combined collision rates of the HOV and its adjacent lane were higher for the HOV facility with limited access." The conclusions presented follow:

- HOV facilities with shoulder width greater than 8 feet displayed significantly lower collision rates regardless of access type.
- The analysis of total width and crash rates indicates HOV lanes with continuous access may result in lower collision rates, given the same total width of right-of-way.
- Limited-access HOV facilities with a combination of short ingress/egress length and close proximity to the nearest on/off-ramps tends to exhibit markedly higher collision rates than other limited access freeway segments.

HOV Facilities Extant in the U.S. (2008)

[*A Compendium of Existing HOV Lane Facilities in the United States*, FHWA HOV Lane Performance (DTFH61-06-D-00006), prepared by Booz-Allen-Hamilton and HNTB, Dec 2008]

This inventory of HOV facilities in the U.S. conducted in 2008 accounted for a total of 345 HOV facilities. California had the most such facilities, at 88, followed by Minnesota (83), Washington State (41), Texas (35), and Virginia (21). The inventory included the following types of HOV facilities: bus lanes/busways; concurrent (median, right side, second lane on one-way urban arterial); contraflow facilities; dedicated curb lanes; high-standard arterial; high-occupancy toll or HOT lanes (reversible, concurrent); reversible lanes; and separate dedicated roadways. There were a number of separation designs note during the inventory, including: barriers; buffers; cones; dashed line + broken diamond pavement marking; limited-access highway; moveable barrier; none; painted stripe(s); pylons; standard dashed line; traveled lane edge line.

The vast majority of HOV facilities had only one HOV lane in each direction. The longest active HOV facilities were identified in Miami, FL (I-95 between SR 112 and Gateway Blvd – 116.0 lane-miles, 58.0 route miles) and Los Angeles County, CA (I-405 – 105.2 lane-miles, 52.6 route miles). The most common separation technique used for all HOV facilities is the painted stripe; 118 (34 percent) of all such facilities fall into this category. Sixty (17%) of all HOV facilities inventoried were developed with buffers (e.g., linear, diagonally striping on the roadway) used to constrain movements (i.e., limit ingress/egress to pre-determined locations) between the HOV lanes and GP freeway lanes. Buffers do not totally prevent "at will" movements between the HOV lanes and GP freeway lanes.

The inventory identified 45 HOV facilities (13 percent) in the U.S. developed with barriers that constitute "limited-access" HOV facilities (also referred to as "intermediate access"). Barriers effectively restrict ingress/egress to specific locations along the length of the HOV facility, where an opening is provided to permit transitional movements between the HOV facility and GP freeway lanes. Six barrier-type HOV facilities are based on "moveable" barriers used to create an extra lane in the peak direction of travel, which, in effect, is a protected contraflow lane.

The most common type of HOV facility noted during the inventory was the concurrent (median) defined by a painted stripe; 187 facilities (54 percent) fell into this category. Concurrent (median) HOV facilities allow permitted motorists to use the inside lanes of a freeway, i.e., lanes in the center or median, simultaneously and parallel to the GP freeway lanes. Concurrent (median) HOV facilities can be separated simply by a solid white or yellow lane, allowing motorists to move freely between the HOV lanes and GP freeway lanes. This is the principal design of HOV lanes currently established within The Spine Corridor. As noted above, concurrent (median) HOV facilities also can be defined, even separated, by buffers and physical barriers. These features are intended to constrain or "limit" access (ingress/egress) to the lanes at locations, where the buffer or barrier does not exist.

Separation of Toll Lanes and Free Lanes (2007)

[Best Practices: Separation Devices between Toll Lanes and Free Lanes, Center for Transportation Research, The University of Texas at Austin, for TxDOT, FHWA/TX-07/0-5426-1, October 2006, Rvsd November 2007]

This report examines three basic categories of separating or delineating separation of vehicles operating in managed lanes versus mixed traffic operating in GP freeway lanes. Managed lanes, the report indicates, provide a means of expanding the potential of current highway infrastructure to accommodate greater travel. HOV and HOT lanes allow transportation engineers to manipulate roadway operations and achieve varying LOS. To manage traffic in special lanes, the lanes must be separated from the GP freeway lanes. HOV lanes have been used widely with considerable success in terms of operational advantages and safe travel, and this report seeks to determine whether safety and cost factors of HOV lanes can be applied to managed lanes, here specifically referring to HOT lanes.

The project included convening an "expert panel" to discuss conceivable factors that may influence the choice of treatment for delineating managed lanes. The discussion first focused on the implications of differing roadway conditions and how those conditions would affect the choice of a delineation treatment. The final list of roadway variables is shown below:

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.

Secondly, the panel examined and considered the various inherent characteristics of each type of treatment – characteristics that would not change from site to site. The final list of common characteristics is show below:

Entry/Exit Considerations,
Enforceability/Compliance,
Cost,
Safety,
Aesthetics, and
Constructability.

The three basic categories adopted for consideration during these analyses were: concrete barrier, pylon posts, and painted buffers. The result of the expert panel's exercise is a table of comments and responses regarding each of the conditions and characteristics cited above. This table is included as **Attachment B**.

Under the subject of Safety, presented here as **Table 1**, the panel addressed "Safety for Managed Lane Users," and "Safety for Users of Non-Managed Lanes." It is readily apparent from the '+s' and '-s' that the Concrete Barrier was most favored as a design treatment. However, there are two "ifs" that deserve attention. These "ifs" relate directly to the means of access, indicating that entry into the barrier-separated managed lanes was considered a significant challenge and needed serious, careful consideration. The primary issues associated with the painter buffer and pylon (or post) relate to the weaving activity essential to the ingress and egress of these types of lanes. This apparently was seen almost as a fatal flaw, when addressing the question of safety of operations.

Table 1 | Expert Panel Safety Analysis

	Concrete Barrier	Buffer	Post
VIII. Safety			
1. Safety for managed lane users	**Yes** + Provides protection from swerving vehicles from adjacent general-purpose lane. + Provides protection from high-speed differentials with adjacent general-purpose lane. + If access to facility is provided via t-ramps, no weaving is necessary. – If direct connections are not provided, drivers face the potential of striking the edge of the barrier when entering the facility.	**No** – No protection from swerving/wayward vehicles – Drivers must weave across main lanes to access managed facility.	**No** – No substantial protection from swerving/wayward vehicles. – Drivers must weave across main lanes to access managed facility.
2. Safety for users of non-managed lanes	**Yes** + Provides protection from swerving vehicles from managed lanes. + Provides protection from speed differentials with managed lane. + If access to facility is provided via t-ramps, no weaving is necessary.	**No** – No protection from swerving/wayward vehicles – Main lane motorists will have to deal with managed-lane users weaving across the main lanes.	**No** – No substantial protection from swerving/wayward vehicles – Main lane motorists will have to deal with managed-lane users weaving across the main lanes.

Weaving was seen as a problem for the barrier-separated lanes, if the entrances and exits are accessible to the GP freeway lanes. This treatment was seen as most safe with provisions for direct access via a ramp. The T-ramp, or direct HOV (DHOV) ramp, was seen as an example of safe ingress/egress, as it permitted motorists to enter and exit without the "tricky maneuvering involved with weaving." The panel concluded that concrete barriers, providing a barrier-separated operating environment, is generally accepted as the safest treatment; "neither [the] post nor buffer styles of delineation is as safe as concrete barriers." Nevertheless, a safety concern was raised relative to the accommodation of disabled vehicles, especially in sections where the stopping sight distance is limited. Because of the possibility of crashes occurring within the concrete barriers, the panel "…strongly recommended using a cross section of no less than 18 feet [5.5m]."

The panel found no significant distinctions between buffers and posts as methods of delineating managed lanes relative to safety concerns. The posts were viewed as slightly more effective, as motorists may perceive them to be potential damaging to the vehicle. Also, the use of post, or pylons, generally includes greater control of ingress and egress locations, resulting in a reduction in the amount of vehicles weaving through mixed traffic of the GP freeway lanes to enter and exit the dedicated travel lane. The post treatment also may make it more likely for a motorist to not attempt to avoid a crash, due to reluctance to cross through the line of posts. Although this issue is not associated with a painted buffer, weaving maneuvers for entrance or exit purposes, especially if a high speed differential is present, can result in crashes impacting both the managed lanes and GP freeway lanes. Nevertheless, the buffer-separated facility offers the opportunity to avoid a collision or object, if the adjacent GP freeway lane is clear

This report also includes a comparison of the findings, conclusions, and recommendations of the "expert panel" with information available through published sources. The literature review conducted for this report generally supports the conclusion of the panel that concrete barrier-separated managed lanes would be safer. This is particularly true when the speed differential between the managed lanes and GP freeway lanes is high. The literature also agrees that a physical barrier precludes violators and random ingress/egress activity. However, a continuous barrier is seen as a potential disadvantage relative to response times and operations of emergency vehicles.

Although one source noted that at-grade access to managed lanes from the GP freeway lanes was acceptable "…when cost or right-of-way limitations preclude the use of direct-access designs [ramps]," the report states "…no source recommends the use of at-grade access…" if grade-separated, direct access is feasible. Direct connections largely eliminate complicated weaving maneuvers in congested traffic that potentially can degrade traffic flow and impact safety. The literature review largely agrees with the expert panel regarding the issue of weaving associated with painted buffer- and post-separated managed lanes. Neither treatment is compatible with the speed differentials between the managed lanes and GP freeway lanes, which poses a challenge for motorists operating in both environments. Even so, these "barrier-lite" type of treatments do have the advantage of being more accessible for use by emergency and maintenance vehicles. The comparison of the expert panel with the literature resulted in the following conclusions regarding operational safety of managed lanes:

- 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 [5.5m] 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.
- The Panel generally found posts to be the least favorable type of delineation, but could be useful as a transition to barrier-separated facility.

HOV Lane Safety: Before and After (2007)

[Contiguous HOV Lane Safety: A Before and After Comparison of Accident Rates, Conference Paper, Carol Pearce and David Stanek, July 2007]

This paper points out that research studies associated with buffer- and barrier-separated HOV lanes found crashes to be concentrated at the ingress/egress locations. The paper focused on safety and crash rates associated with concurrent, contiguous operations before and after installation. Two freeway corridors, HOV lanes present and operational were evaluated. The evaluation looked at: the location of collisions (e.g., shoulder, left lane of freeway, etc.); collision type (e.g., sideswipe, rear end, etc.); maneuver immediately preceding the collisions (straight, weaving/changing lanes, etc.); and variations in traffic levels and congestion before and after construction of the facilities.

Findings and conclusions drawn from the study indicate there was no relationship between the rate of crashes in the corridor, where the facilities are located, and the addition of the contiguous, concurrent-flow HOV lanes. A further conclusion was that notable increases in the overall crash rate for the facilities evaluated was related to the level of congestion, rather than the evaluation factors cited above. On the other hand, although the increase in crash rates after establishment of the HOV facilities was not closely related to lane operations, the analysis indicated the limits of the HOV lane seemed to affect the level of congestion, which indirectly did affect crash rates. This study concludes that crash rates are influenced more by congestion than the presence or non-presence of HOV facilities. The crash data examined showed no definitive changes in collision type, movement preceding collisions, or other operating factors "…that would support the contention that contiguous HOV lanes affect traffic safety."

HOV Lane Safety without Physical Separation (2007)

[Safety of High-Occupancy Vehicle Lanes without Physical Separation, Thomas F. Golob, et al, for Caltrans, October 2007]

This study compared 14 months of crash data for an HOV operation in greater Los Angeles area with similar data for six years prior to opening of the HOV lane. The period covered by the examined data was January 1, 1979, through August 31, 1986. The lane is not separated from the GP freeway lanes by a physical barrier. The results of this case study revealed no adverse effect on safety conditions could logically be attributed to the introduction of HOV operations. The study team found the location and timing of traffic congestion was the best explainer of changes the number of crashes and the pattern of crashes. The case study, however, demonstrated that the locations of crashes migrated along the corridor as a response to changes in the location congested areas and the creation of bottlenecks downstream from the HOV project. This suggests that planning and design of HOV/HOT managed-lane facilities need to take into account potential changes in the travel dynamics of the corridor wherein such facilities are established. This particular case study notes that the HOV lane did not degrade safety performance in the corridor, but neither did it improve safety performance.

Considerations for Creating a Managed Lane (2007)

[*Considerations for High-Occupancy Vehicle (HOV) to High-Occupancy Toll (HOT) Lane Conversions Guidebook*, FHWA, Office of Operations, June 2007]

This report notes that differences in right-of-way availability may affect the adopted design standards for a HOT Lane (i.e., managed lane) and the method of separating HOT Lane operations from vehicles operating in GP freeway lanes. It addresses multiple aspects of the physical design of HOT Lanes and summarizes the various benefits and issues associated with each type: barrier separated, buffer separated, contiguous (i.e., concurrent), and grade separated. This report cites three safety considerations when developing the cross-section for a managed lane:

Crash attenuation for the exposed barrier ends at the entrance to the facility,
Transition treatments associated with HOV and GP freeway lanes, and
Adequate access (ingress/egress) opening lengths.

The safety concerns highlighted in this report are summarized in **Table 2**, according to six physical design options to obtain separation. All, except the Non-Separated Shoulder, include a parallel emergency area for disabled vehicles and enforcement.

Ultimately, managing vehicle movements between HOV/HOT managed lanes facilities and GP freeway lanes will determine the effectiveness and safety of managed lanes. The facilities must be well-designed to accommodate ingress and egress, while avoiding unnecessary bottlenecking, violations, and unsafe weaving movements in the GP freeway lanes. The cross-section design (lane and facility geometry) is a critical prerequisite to attaining safety goals, while achieving the desire LOS.

Table 2 | Comparison of Benefits and issues by HOT Lane Separation Type

HOT Lane Separation Type	Benefits	Issues
Concrete Barrier	Safety for General Purpose Lanes	▪ Users feel confined ▪ Limitations on access critical with occurrence of an incident disrupting traffic flow
Flexible Delineators (Pylons)	Unlimited ingress/egress	▪ Motorists able to drive through delineators ▪ Possible hazard for other vehicles from flying delineator
Buffer	Motorists have a way out	▪ Motorists cutting in and out of the buffer-defined facility
Non-Buffer (Painted Stripe)	Motorists have a way out	▪ Safety and enforcement issues associated with free flow in and out of the facility
Non-Separated Shoulder	Provides improved capacity without an dedicated new lane	▪ Confusion of lane use can occur ▪ Lack of emergency pull-outs for disabled vehicles
Grade Separation	Safest, due to exclusive use and limited access	▪ Users feel confined ▪ Expensive

Signage is cited as "a major element in HOT [lane] operations and management." Inadequate signage and the location of such signage, both upstream and downstream of the access locations, is critical to motorists making a timely, informed travel decision. Inadequate signage can compromise facility and vehicle safety; therefore, signage must be such that motorists in the managed lanes and general purpose lanes understand which message should be followed. That is to say, motorists must be able to understand the message intended for their lane, but, also, they need to understand the message for the other lanes. This means signage must be located sufficiently in advance of the need to maneuver to permit motorists adequate opportunity to process and execute the directions obtained from the sign.

The report notes that inadequacy of enforcement signage can contribute to hazardous operation conditions, especially associated with the practice of "lane diving" or lane shifting/weaving, whereby motorists move freely between lanes of a non-barrier separated facility and GP freeway lanes. In fact, it states "One of the biggest challenges facing HOT lane planning and operations is and will continue to be enforcement." A major lesson gleaned during this study is that manual enforcement can be an effective means of controlling access to HOT lanes; even so, it is virtually impossible to assure 100% enforcement. Enforcement is especially critical relative to non-barrier-separated managed lanes, which would have multiple, even infinite, access locations. The report notes that expansion from a HOT lane to a HOT lanes network will stretch manual enforcement capabilities even further and diminish its effectiveness as a deterrent to violations, which creates the potential for a less safe operating environment.

HOT Lane Buffer and Mid-Point Access (2006)

[*HOT Lane Buffer and Mid-Point Access Design Review Report*, Washington State Department of Transportation, Oct 2006]

This Washington Department of Transportation (WSDOT) report provides an overview of buffer and mid-point access designs for HOT lanes operating concurrently with GP freeway lanes. Three design recommendations (cited below) emerged from the literature review and studies supporting this report:

A preferred buffer width between a HOT lane and an adjacent GP freeway lane of 4 feet, with a minimum recommended width of 2 feet, if it is not feasible to provide a 4-foot buffer.

A continuous inside shoulder of 14 feet for enforcement and to serve as a breakdown lane, with a minimum 2-foot inside shoulder width recommended to separate the travel lane from any barrier, if the ideal width is not feasible.

Mid-point access location openings of 1,000 feet per lane change; with a minimum length of 500 feet. For a combined access (allowing both ingress and egress), the length of the access point should be at least 1,000 feet (twice the minimum acceptable lane change distance of 500 feet).

The report addresses safety issues and concerns associated with HOT lanes. The first notable conclusion presented states little research or experience is available to permit conclusive statements regarding safety and the buffer width between the HOT lane and GP freeway lanes. It does note that evidence suggests buffers greater than four feet tend to collect debris. Also, the literature review indicates a concern that some drivers may try to use wider buffers as a breakdown lane, which would present particularly hazardous conditions with high speed traffic operating on both sides of the buffer. A buffer width minimum of two feet is cited from the *FHWA Guide for HOT Lane Development*.

The report notes that a recent report produced by the Texas Transportation Institute (TTI) indicates no definitive conclusions can be reached relative to the safety of concurrent flow, buffer-separated HOT lane facilities.[38] The TTI review of previous studies revealed there is conflicting evidence regarding the safety of buffer-separated HOV lanes. However, TTI notes there seems to be anecdotal evidence that injury crash rates have increased, where such facilities have been installed in Dallas, TX. Nevertheless, the TTI report indicates this increase likely resulted from the speed differential between the HOV lanes and GP freeway lanes.

The report cites a study in Orange County, CA, addressing the advantages and disadvantages of a continuous, concurrent facilities and buffer-separated, concurrent facilities with controls on access. **Table 3** cites the safety-related issues and concerns raised as a result of this study.[39]

The ideal access design would separate ingress and egress locations; this would eliminate potential conflicts between vehicle entering the facility and vehicles exiting the facility. In addition, an auxiliary lane would be provided between HOV/HOT managed-lane facilities and GP freeway lanes to permit motorists to accelerate or decelerate, as appropriate. An added feature might be a shoulder area immediately downstream of the access location to permit enforcement officers a station for observing and monitoring use of the HOV/HOT managed lanes. In the case of right-of-way constraints, the ingress/egress location may be combined and the auxiliary lane excluded. This, however, would require sufficient length to accommodate safe weaving of vehicles entering and departing the facility. If no barrier is installed, the minimum restriction on vehicle transitions between the HOV/HOT managed lane facilities would be a double white stripe, which would change to a permissive dashed white stripe. That being said, this report notes:

Table 3 | Issues and Concerns Associated with Unlimited- and Limited-Access Facilities

Issue/Concern	Unlimited Access	Buffer-Separated Limited Access
Safety	▪ No systematic impact on crash rate ▪ Traffic queued in general-purpose lane can maneuver into HOV lane unexpectedly ▪ Potential for unexpected access of HOV lane creates perception of hazardous operating condition	▪ No systematic impact on crash rate ▪ Concentrates merging and weaving at designated access (ingress/egress) locations ▪ Reduces merging between access locations ▪ Impacts are location-specific
Isolation form Congestion and Incidents in General Purpose Lanes	▪ HOV volumes can spike at congestion hot spots due to HOV traffic shifts into HOV lanes	▪ Minimizes impact to HOV lane operations resulting from traffic disrupting incidents and congestion in general-purpose lanes ▪ HOV lane traffic can be enhanced and operating environment can be increased with addition of left-side shoulder and direct access ramps
Impact on General Purpose Traffic	▪ Weaving (ingress/egress) actions are distributed over the length of the facility/corridor ▪ Concentration of weaving at inappropriate locations or inadequate weave distance exacerbates bottlenecks	▪ Weaving can be concentrated where adequate capacity exists ▪ Limited direct access locations reduces weaving associated with access (ingress/egress) of HOV lane
Driver Expectancy (Regional Consistency)	▪ HOV facility operation is similar to general purpose lanes	▪ Isolated buffer and access treatments may be appropriate when a facility does not connect with other HOV facilities ▪ Buffer and access treatments should be consistent with adjacent facilities
Compatibility with HOV and Potential Transit Operations	▪ Most appropriate when HOV lane is used for general purpose travel in non-peak periods	▪ Buffer treatment may be desired in anticipation of future HOT Lane or Bus Rapid Transit (BRT) operations ▪ Direct access can be provided to further reduce vehicle weaving

> *Extensive research designed to definitively identify the impacts of the different designs does not exist, particularly regarding access design where physical constraints often determine the type of access (combined, vs. separate, whether a weave lane is provided, etc.). In existing facilities, every effort is made to adequately balance the desire for high levels of service in the managed lanes with providing safe and efficient access and separation options.*

This report brings out another important aspect of HOV/HOT managed lane operations: mid-point or intermediate access. It should be noted that this concept is not being contemplated for the HOV/HOT managed lanes facility in the Spine Corridor. A common design of an intermediate access location allows ingress and egress by changing the buffer striping only, in the case of a buffer-separated facility. Prohibitive, solid striping changes to permitted, dashed striping to allow a lane change. Vehicles then may enter or leave within this zone, merging essentially within an auxiliary lane.

[38] *Crash Data Identify Safety Issues for High-Occupancy Vehicle Lanes in Selected Texas Corridors*, Texas Transportation Institute, 2004. Project Summary Report 04434S.

[39] Orange County HOV Lane Operations Policy Study, Orange County Transportation Authority, 2002, Page 40.

A barrier-separated HOV/HOT managed-lane facility also can have an intermediate access location(s) with breaks in the barrier to permit the transit of vehicles into and out of the HOV/HOT facility.

MANAGED-LANE FACILITY PERFORMANCE (2005)

[*Monitoring and Evaluating Managed Lane Facility Performance*, Technical Report, Texas Transportation Institute, for TxDOT, FHWA/TX-06/0-4160-23, November 2005]

This Technical Report was prepared to provide information relating to the best performance monitoring and evaluation practices and principles explicitly employed with regard to managed-lane facilities, specifically, in the context of this report, value-priced and HOT. Although the focus of this report is on performance, some information is provided about safety and evaluating the safety of various managed-lane treatments. Ultimately, the report concludes that, in general, the creation of passenger-focused, managed-lane facilities has the primary intent of increasing person throughput. Safety is addressed as a secondary interest and then primarily to "confirm no adverse impacts from implementation of the managed-lane facility." It is noted that crashes associated with managed lanes occur infrequently; therefore, a lengthy evaluation period is necessary to acquire a reasonable dataset for analysis. The implication here being that the facilities have not been the objects of adequate attention nor time commitments required to compile a useful body of knowledge to evaluate safety effects.

Similarly, although, HOV facilities have a more extensive history of performance monitoring and evaluation, these facilities also are implemented with the primary purpose of increasing person throughput. Safety and environmental concerns (e.g., air quality) typically are secondary interests, although some HOV projects have been implemented to achieve safety goals and objectives. In contrast, the report notes that freight-focused managed-lane facilities often are undertaken with a primary interest in improving safety and achieving benefits with respect to preserving pavement infrastructure. Thus, while this is an extensive dissertation that presents lengthy discussion of evaluation methods, such as goals, objectives, and performance measures, relating to managed lanes, it does not represent a significant contribution to the subject of safety.

MANAGED LANES PRIMER (2005)

[Managed Lanes, A Primer, Federal Highway Administration, FHWA-HOP-05-031]

This Primer was prepared to provide local transportation officials with information about managed lanes as a mobility strategy. It provides a definition of managed lanes, presents managed lanes success stories, identifies issues and challenges unique to this type of project, and examines the future of managed lanes as a transportation mobility solution. First off, the Primer couches the issues of transportation capacity by pointing out the vehicle miles traveled nationally increased 70 percent from 1985 t0 2005, but highway capacity grew by only 0.3 percent. In addition to various constraining factors, like increased costs, right-of-way constraints, environmental concerns, and societal impacts, the Primer notes that many transportation agencies "…are grappling with a serious transportation funding crisis."

Managed lanes are defined as a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions.

Managed lanes is one approach to make more effective and efficient use of existing highway capacity. This is accomplished by engaging in three primary actions: pricing (i.e., tolling and value pricing), vehicle eligibility (e.g., minimum occupancy), and access control (i.e., limitations on entry to manage congestion and operational conditions). These actions are implemented to regulate traffic flow in essentially a "freeway within a freeway." Travel activity on the managed lanes is managed to respond to growth of traffic in the corridor and changing demand; this is a continuously active practice to optimize operational conditions to achieve and maintain "free-flow" speeds. This requires careful considerations of project goals and evaluation of the unique characteristics of the corridors where facilities are planned.

Developing, implementing, and operating managed lanes has proven effective for mobility improvement in many communities in the U.S. and around the world. Nevertheless, there a number of critical issues that have come to light, including:

- access design [an safety],
- driver information and signing,
- enforcement,
- revenue generation and equity,
- legislative authority,
- new institutional arrangements,
- analysis techniques and demand forecasting models,
- design flexibility,
- integrated transportation opportunities, and
- technology.

Significant for the issues and concerns voiced relative to the Spine Corridor:

- Access design impacts operational conditions and affects the ability to manage lanes through modifications to operating strategies.
- The number and spacing of access points increases the complexity of operations and makes enforcement more challenging.
- Spacing of access points, particularly relative to freeway on- and off-ramps, affects the length of weave/merge sections with the potential to impact the safety and operating conditions of the managed lanes and the GP freeway lanes.
- Combinations of pricing, vehicle eligibility, and/or access location, such as would be associated with a HOV/HOT lanes facility, requires information be communicated to motorists in a clear, concise manner, while avoiding information overload. Motorists must process standard and special (i.e., managed lane-specific) directional and informational signs quickly and efficiently to be able to operate vehicles in a safe manner. Motorists unfamiliar with the corridor may need to make quick decision on whether or
- Not to use the facility, which can be particularly challenging and impact safe operations of the managed lanes and the GP freeway lanes.
- Complex operating strategies involving vehicle eligibility, vehicle occupancy, and pricing makes enforcement more challenging.

OPERATIONS CONCERNS AND MITIGATION MEASURES (2005)

[12th International HOV Systems Conference: Conference Proceedings, Breakout Session – Operation Updates, FHWA, April 2005]

A study presented relating to HOV facility use during an Operation Pilot Project sponsored by WSDOT indicated there was considerable excess capacity in the HOV lanes in evening periods. The question of allowing SOVs to operate in the lanes during these periods revealed potential safety concerns, but also revealed a key advantage of non-barrier HOV facilities that allow easy and convenient access by all vehicles in the travel corridor. Specific roadway improvements, such as ground-in, rumble-strips and profiled edge striping, were implemented.

A study presented regarding Houston HOV facilities documented crashes on HOV lanes and the characteristics of those crashes. The study also included an attempt to compare the safety of HOV land with non-HOV GP freeway lanes. It was found that crashes in the HOV lanes typically peaked during the congested periods and peaked more than the GP freeway lanes. Not too surprising, single vehicle crashes accounted for 30 percent of crashes in HOV lanes, but only 24 percent on GP freeway lanes. This likely could be due to the fact that HOV lanes support a single lane of traffic, minimizing the opportunities for multi-vehicle crashes. Also, not surprising, speeding

accounted for over 50 percent of crashes on both the HOV (53%) and GP freeway lanes (56%). The slightly higher percentage for the GP freeway lanes likely is related to more opportunities to collide with other vehicles in a congested stream of mixed traffic. Another finding likely to be associated with the single line of traffic in the HOV lanes, following too close accounted for a greater percentage of crashes on HOV lanes (5%) compared to the GP freeway lanes (3%).

Findings presented from the Houston study included the tentative conclusion that HOV lanes are safe relative to GP freeway lanes. But, the presenter also notes that there "…appears to be a safety trade-off between barrier facilities and concurrent flow lanes." Future research was necessary to determine the characteristics of this trade-off and how the two types of facilities affect different groups of drivers.

Crash Occurrence in Barrier-Separated HOV/HOT Facilities (2005)

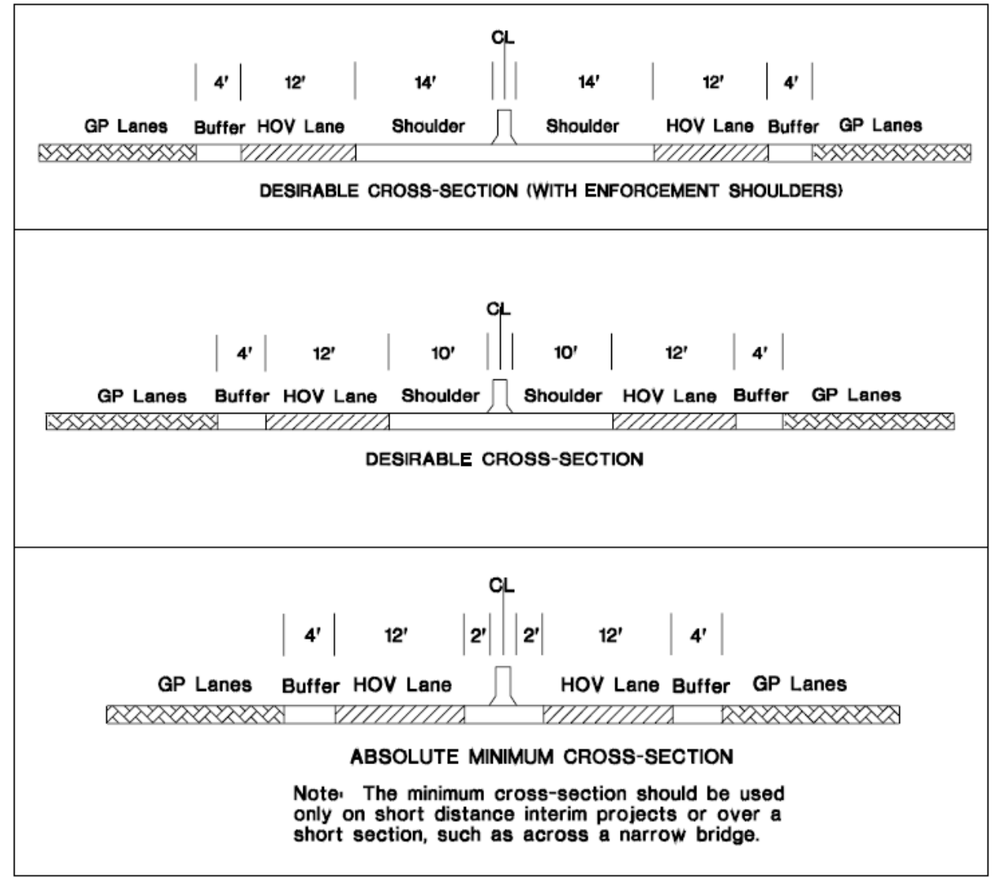
[*Crash Data Identify Safety Issues for High-Occupancy Vehicle Lanes in Selected Texas Corridors*, Project 0-4434: Safety Evaluation of HOV Lane Design Elements, Texas Transportation Institute (TTI), March 2005]

The objective of this study was to gain greater understanding of "…safety issues associated with HOV lanes, particularly buffer-separated concurrent flow HOV lanes." Although the study principally was looking at options associated with moveable barriers, the conclusions shed some light on the safety performance of fixed-barrier facilities. The report states available studies indicate safety performance of buffer- and barrier-separated, concurrent-flow facilities is similar to other types of HOV lane facilities (e.g., concurrent, contiguous, concurrent-flow projects). It generally is recognized that crashes in separated facilities do not disrupt operations of the GP freeway lanes (discounting "rubber necking," of course) and vice versa. Preparers of this report note there are two primary concerns often raised relative to separated HOV/HOT facilities: (1) the speed differential created between the separated facilities and GP freeway lanes, and (2) the inability of vehicles operating within the facility to maneuver around or avoid traffic interrupting incident.

This study relied on a before-and-after focus to identify the change in crash rates subsequent to establishment of buffer-separated HOV lanes in the IH-35E North and IH-635 corridors in Dallas, TX. The study team found the crash rate increased 56 percent in the IH-35E North corridor and 41 percent in the IH-635 corridor. Three key findings were identified: (1) the injury crash rate increased; (2) crashes primarily occurred within the HOV facility and the immediately adjacent GP freeway lanes; and (3) the increase in crashes likely resulted from the speed differential between the HOV lane and GP freeway lane. The speed differential results from congestion in the GP freeway lanes slowing the operating speed compared to faster traffic in the HOV lane.

The speed differential creates problems for motorists exiting the HOV lane, as there few gaps available in the adjacent, congested GP freeway lane and other lanes. The study team also found that most of the crashes associated with the buffer-separated HOV facility with intermediate access locations occurred at or near the ingress and egress locations. The team also indicated that, due to the speed differential, it would be advisable to identify and implement actions that would reduce speeds at the ingress and egress locations, specifically on the HOV lane. The report provides recommend cross-sections for future HOV projects that were developed in a prior study, *Guidance for Future Design of Freeways with High-Occupancy Vehicle (HOV) Lanes Based on an Analysis of Crash Data from Dallas*, which is summarized below (**Figure 5**).

Figure 8 | Buffer-Separated, Concurrent Flow HOV Lanes Desirable/Minimum)



The study team believes the recommended cross-sections will aid in preventing the type of crashes noted during the analysis. A specific recommendation addresses the need for space to bypass a slowing, stalled, or disabled vehicle in the HOV lane:

> *The minimum cross-section provides enough room for two 8-foot-wide vehicles to be in the HOV lane area (inside shoulder, HOV lane, and painted buffer) of the freeway without encroaching on the general-purpose lanes.*

ISSUES AND OPTIONS FOR ENFORCEMENT (2004)

[HOV Lanes: Issues and Options for Enforcement, Final Report 552, ADOT, June 2004]

This report, citing a Minnesota Department of Transportation (MinnDOT) study, indicates the rate of traffic incidents (i.e., crashes) associated with buffer-separated HOV lanes is roughly twice that of barrier-separated HOV lanes. The cited study indicates two to three incidents per million miles of travel for the buffer-separated facility versus ≈1.4 incidents for the barrier-separated facility.[40] That being said, the report also notes that barrier-separated facilities "…are used less often, and for shorter distances." Also, barriers limit entrance, particularly exit, which is a discouraging aspect for commuters when exits are not convenient to their desired destination. The remainder of this study focuses on enforcement conditions and designs and procedures for enforcement.

Key Findings

- No technology exists that can fully automate HOV occupancy enforcement, because no technology exists that can see through metal vehicles and pick out the people inside.
- Of the factors that limit the ability to see inside a vehicle, the most pernicious is window tinting, because of the threat it poses to law enforcement. Opaque auto glass tinting can hide not only a weapon, but also the person reaching for it.
- Adequate enforcement requires extensive space in the median. In many instances it is not feasible to provide this space.
- Current statutes that require officers to have vehicles pull over to the right are inappropriate for HOV enforcement.

GUIDANCE FOR FUTURE HOV FACILITY DESIGN (2004)

[Guidance for Future Design of Freeways with High-Occupancy Vehicle (HOV) Lanes Based on an Analysis of Crash Data from Dallas, Texas, Texas Transportation Institute for TxDOT and FHWA, FHWA/TX-05/0-4434-P1, May 2004]

This report, based on crash data, has been created to provide guidance for future design of HOV facilities on freeways. The IH-635 facility in Dallas is highly congested and used frequently for short trips within the urban area. This travel characteristic results in excessive weaving associated with entry and exit of the HOV facility, and the presence of numerous freeway on/off ramps contributes to the weaving activity. The heavily congested conditions makes it difficult for motorists to find gaps in the GP freeway lane adjacent the HOV lane to exit the facility. Also, the continuous, contiguous, concurrent-flow, barrier-free HOV lane is difficult to enter, as motorists must weave to the lane then quickly accelerate up to the higher speed of the less congested facility. In both situations, the speed differential appears to be a primary factor affecting crash occurrence.

This report suggests six specific corridor characteristics to be utilized as guidance for choosing to implement a buffer- or barrier-separated, concurrent-flow HOV lane, specifically:

- Radial corridor,
- Long distance trips,
- Minimum cross-section can be used for interim installations,
- Minimum cross-section can be used across a narrow bridge structure or around columns,
- Good freeway ramp spacing that meets or exceeds current AASHTO guidelines, and
- Opportunity for enforcement locations.

The cross-sections developed as a result of this TTI study for TxDOT were incorporated into a subsequent TTI study, *Crash Data Identify Safety Issues for High-Occupancy Vehicle Lanes in Selected Texas Corridors*, as summarized earlier (refer to **Figure 3)**. The study team explains the functioning/operation of the recommended cross-sections in the following manner. The desirable cross-section with inside 10-foot shoulder, HOV lane, and painted buffer enables two 8-foot-wide vehicles to operate safely within the HOV facility, as may be required, without encroaching on the GP freeway lanes. This cross-section provides sufficient space for an entering vehicles to accelerate, while allow any upstream, oncoming vehicles to bypass on the inside shoulder, if necessary. The wide shoulder of the desirable cross-section would enable motorists to better accommodate the speed differential between the HOV lane and the GP freeway lanes. Exiting vehicles could slow or even stop, if necessary, to take advantage of gaps in the GP freeway lanes; the shoulder, in this case, would provide sufficient space for another HOV vehicle to pass. The cross-sections, in effect, support the need for acceleration and deceleration, as required, to accommodate ingress and egress, respectively.

The report notes there are two additional design/operational treatments to consider in addition to the overall cross-section.

- Endpoint/Terminus of HOV Facility
  - Terminating the HOV/HOT facility in an area of congestion is not recommended.
  - Provide, as may be possible or feasible, a dedicated travel lane at the facility terminus and any intermediate egress location to assure ample time for vehicles exiting the facility to transition into the mixed flow of the GP freeway lanes.
- Ingress/Egress Functions
  - Direct connector ramps are desirable for entering or exiting the HOV/HOT facility rather than weaving through the GP freeway lanes.
  - Allow at least 800 feet for any weaving maneuvers to enter and exit the HOV/HOT facility.
  - Maximize the distance between ingress/egress locations and the nearest on/off ramps of the freeway to accommodate weaving vehicles.
  - Merge areas for ingress/egress locations should be 1,300 to 1,500 feet in length.
  - Traffic volumes should be used as the guide for merge area lengths.
  - Refrain from locating ingress/egress points on horizontal or vertical curve, but, if necessary, account for speed differentials when evaluating needed sight distance.
  - The preferred location for facility ingress is after an exit ramp to preclude motorists diving toward the HOV lane soon after entering the freeway stream; similarly, egress locations should not immediately precede a freeway exit.

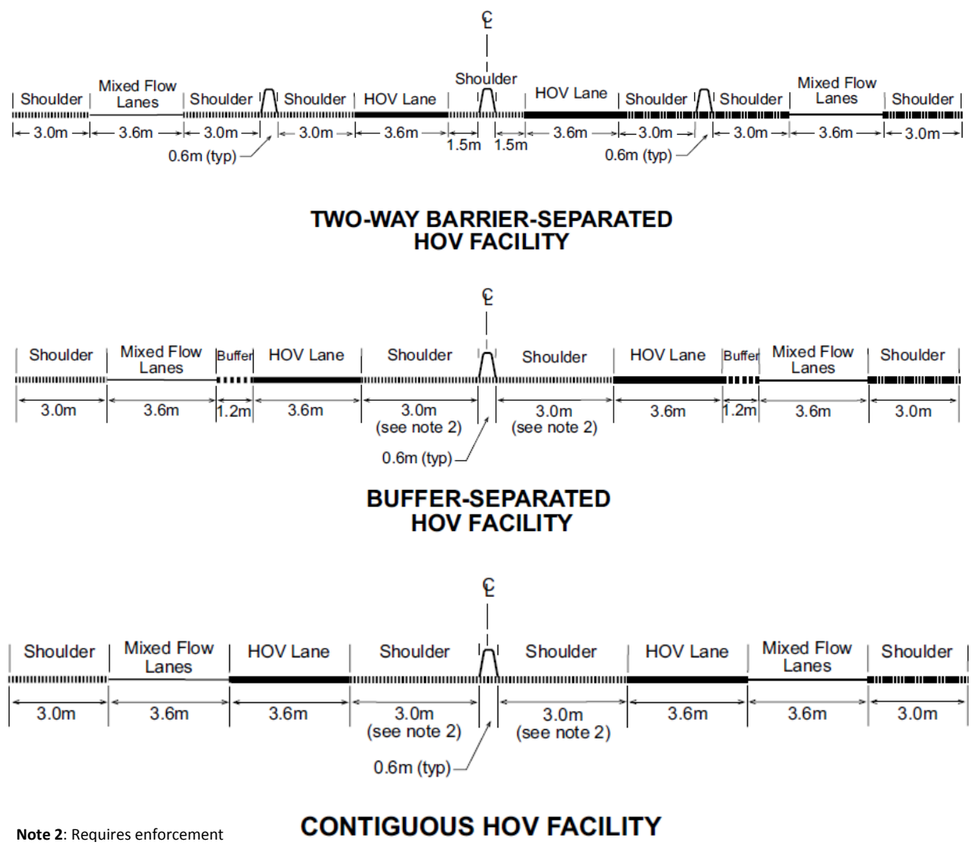
HOV PLANNING, DESIGN, AND OPERATIONS GUIDELINES (2003)

[High-Occupancy Vehicle Guidelines for Planning, Design, and Operations, Caltrans Department of Transportation Division of Traffic Operations, August 2003]

This document addresses barrier-separated, buffer-separated, and contiguous HOV facilities, all based on a concurrent-flow operation. Barrier-separated facilities are divided into two-way, barrier-separated HOV facilities and one-way, reversible barrier-separated HOV Facilities (the latter has not been identified as an option under consideration for The Spine Corridor). The report describes barrier-separated HOV facilities as having the following advantages: easy to enforce, easy to manage incidents, no interference from mixed-flow GP freeway lanes, low violation rate, and high level of driver comfort. The three cross-sections are shown in **Figure 6**.

[40] Cambridge Systematics with URS, Inc. *Twin Cities HOV Study Final Report.* (Minnesota Dept. of Transportation; February 2002), 5-4.

Figure 9 | Alternative Cross-Sections for HOV Facilities



Note 2: Requires enforcement

Traffic operating on a buffer-separated HOV facility is segregated from GP freeway lanes by a buffer generally 1.2m wide or less (nominal 4 feet). Wider buffers are not desirable, as they may be perceived by motorists as refuge areas, which can result in hazardous driving conditions for traffic in both the HOV and GP freeway lanes. The typical section shown in **Figure 4** includes a 3m-wide shoulder (nominal 10 feet) to the left (median side) of the HOV lane. The Caltrans report notes that buffer-separated HOV facilities generally provide motorists with better LOS compared to contiguous HOV facilities. The separation provides higher driver comfort and extra margin of safety by providing additional area for maneuvering, and it lessens potential impacts deriving from incidents occurring on the adjacent GP freeway lanes.

Caltrans notes that contiguous HOV facilities normally are associated with short duration, high-volume, peak commute travel demand. These facilities do not offer any separation, aside from a delineating pavement striping, from traffic on contiguous GP freeway lanes, primarily due to limited right-of-way. Users of the HOV lane are free to enter and exit the lane throughout the length of the facility. No design details or special accommodations are required to facilitate ingress/egress, except for pavement striping and signage at the beginning and end of the HOV facilities. A typical cross-section for a contiguous HOV facility operating concurrently with GP freeway lanes is shown in **Figure 4**.

The Caltrans report indicates that direct connector ramps are appropriate to facilitate seamless freeway-to-freeway movements. A decision to pursue this operational solution would depend on:

- Peak-hour volumes on the HOV lanes,
- Available right-of-way along the freeway and within the interchange area,
- Need to alleviate congestion bottlenecks resulting from HOV lane egress and weaving movements across mixed-flow traffic,
- Various issues associated with LOS and travel-time savings, and
- Safety compared to merging requirements, as vehicles exit the HOV lanes into mixed traffic of the GP freeway lanes.

Emphasis appears to be on operational issues and funding, as there is little information available regarding the safety benefits of direct connectors versus at-grade transitions.

General guidance regarding signage and markings associated with HOV facilities states “much of HOV signs and markings relate to enhancing safety for the motorists.” Specific guidance is provide regarding signage associated with HOV facilities:

- Signage is necessary to alert drivers of differential speeds between the HOV lanes and adjacent GP freeway lanes.
- Signage needs to make clear that passing opportunities are constrained and discourage frequent weaving and merging across the delineating striping or buffer zone to pass slower vehicles.
- Signage and markings must be carefully considered to assure not only the typical commuter but also the occasional user can effectively operate on the HOV facility.

Extensive guidance is provided regarding the information, positioning, and maintenance of signage and markings for various type of HOV facilities.

Enforcement raises numerous issues when considering the type of HOV facility. While a paved median and enforcement area is the preferred option of new HOV facilities, right-of-way limitations can stifle efforts to create such areas to support operations of existing HOV facilities. The lack of inside shoulders can have an adverse impact on safety and overall freeway operations. Enforcement, the degree to which there will be enforcement, and safe implementation of the adopted enforcement level also must be a consideration in the design and operation of HOV facilities. The single-stripe barrier creates separation, but this type of treatment may limit enforcement capabilities, due to a requirement for the violator to exit the HOV lane into mixed traffic of the GP freeway lanes. The wider, painted buffer presents a similar challenge, and it is crucial that the buffer be no wider than 1.2m (nominal 4-feet) to prevent the illusion it is a safe place to stop.

A physical enforcement action requires the violator and enforcement official to exit a single-stripe or buffered HOV lane, the two vehicles must weave across the GP freeway lanes, across congested, mixed-flow traffic to the right shoulder of the freeway. This not only poses safety risks to the two vehicles and traffic in the mixed-flow GP freeway lanes, but it is likely to result in congestion. The potential for congestion, in and of itself, creates safety issues for missed-flow traffic traveling at high speeds. Therefore, the potential impacts of enforcement must be weighed against the benefits to be attained in the operations of the HOV facility. Physically-separated HOV lanes with a fixed, permanent barrier requires additional areas to assure safe operation of the HOV facility, safe enforcement activities, and accommodations for emergency vehicles, as necessary. The cross-sections shown in **Figure 4** incorporate nominal

10-foot shoulders complementing the HOV lane, which can minimally support enforcement needs. The Caltrans report states "The optimum design is the availability of adequate enforcement areas in the median. Where existing facilities do not have these enforcement areas or new facilities are not designed with them, it can be expected that enforcement on the facility will be challenging."

INTERIM MANUAL FOR MANAGED LANES (2003)

[Interim Manual for Managed Lanes, Texas Transportation Institute for TxDOT, Report 4160-14 (FHWA/TX-04/4160-14), October, 2003]

This research project was undertaken to (1) investigate the complex and interrelated issues associated with the operation of managed lanes using various operating strategies and (2) develop a Managed Lanes Manual for the Texas Department of Transportation (TxDOT). The project represents three years of research to aid TxDOT in making informed planning, design, and operational decisions regarding managed lanes. The research examined a variety of techniques and measures for expediting traffic flow, including:

Separated Two-Way HOV Lanes,
Concurrent Flow HOV Lanes,
Contraflow HOV Lanes,
Value-Priced Lanes and High-Occupancy Toll (HOT) Lanes,
Exclusive Busways,
Exclusive Truck Lanes,
Separation/Bypass Lanes,
Lane Restrictions, and
Dual Facilities (Inner roadway for light trucks/cars; Outer roadway for all vehicles – for trucks/buses/cars).

The report notes that "the characteristics that matter most to the driver are speed of travel, safety, comfort, and convenience." Although, little information is provided regarding the safety of any of the investigated facility types, and no safety information is provided relative to the design criteria for a managed lane facility. Nevertheless, recommendations are sometimes supported with comments that the specified criteria are needed "…to assure safety…" without supporting evidence or data analysis.

The two configurations of interest for the purposes of this research are Concurrent-Flow HOV lanes and Value-Priced Lanes and High-Occupancy Toll (HOT) Lanes.

Concurrent-Flow, Managed-Lane Facilities

This type of facility generally is not physically separated from the GP freeway lanes. Concurrent-flow HOV lanes generally are located in the median area of highways. Pavement markings commonly are used to delineate these lanes from the GP freeway lanes. Restrictions on use during peak periods commonly promotes more expeditious travel by eligible vehicles. Unlimited ingress and egress to the HOV lanes is a common operational mode, although limited-access is preferred for these types of facilities from the stand point of enforcement. Restrictions on entry/use often are lifted during off-peak periods to expanding the capacity of GP freeway lanes. Key design components of concurrent-flow, managed-lane facilities are outlined below:

Desirable inside shoulder widths contiguous with the median barrier is 10 to 14 ft (3.0 to 4.2 m) for enforcement purposes, but can be less depending on other project constraints (e.g., right-of-way, electronic enforcement).

A concurrent-flow, managed-lane should adhere to the design standards of the GP freeway lanes, which generally are 12-foot (3.6 m) travel lanes.

The desirable buffer width is 4-ft (1.2m); buffers between 4 ft (1.2 m) and 8 ft (2.4 m) should be avoided between the concurrent-flow, managed-lane and adjacent GP freeway lane, as this range may encourage unsafe use of the shoulder as a breakdown or emergency stopping area.

The desirable cross-section for a two-way, concurrent-flow, managed lane includes median barrier, a shoulder (or lateral clearance), managed lanes, and painted stripe or painted buffer to separate the managed lane from the GP freeway lane creating a general design envelope of 54- to 62-ft (16.3 to 18.8 m). Reducing the design envelope to as narrow as 34-ft (10.3 m) may be justified under special circumstances, such a reduction could adversely impact the safe and efficient operation of a facility.

Three different design scheme for concurrent-flow, managed-lanes are shown in **Figure 7**.

Exclusive Two-Way Managed Lane Facilities

Exclusive two-way, managed-lane facilities, or limited-access facilities, are physically separated from the GP freeway lanes, usually by concrete barriers.[41] As this type of facility generally is developed to permit the imposition of value-pricing or tolls, exclusive two-way managed-lane facilities generally remain exclusive throughout most of the day. This type of facility is controlled by limiting access to the beginning and ending of the lanes, although, sometimes, intermediate access points. Intermediate access points permit value-pricing for individual segments and allows access to locations along the route of the facility. The facilities may include direct ramps to overcrossing arterial roadway and other exclusive ingress and egress treatments, e.g., connector ramps from intersecting highways. Key design components of two-way, limited-access, managed-lane facilities are outlined below:

A 2- to 4-ft (0.6 to 1.2 m) lateral clearance should be provided adjacent to the median barrier. As a minimum, a shared median shoulder 10-ft (3.0M) wide would be necessary; however, this treatment would only be applicable for two-way ramps, short sections of roadway, low-volume segments of the facility, or other lower speed conditions.

Operating lanes should be adhere to the design standards of the 12-foot GP freeway lanes.

A 2- to 4-ft (0.6 to 1.2 m) lateral clearance should be provided adjacent to the barrier separating the managed lane(s) from the adjacent GP freeway lane, and a similar lateral clearance should be provided on the GP freeway land side of the barrier.

The cross-section for a two-way, concurrent-flow, managed lane includes median barrier, an inside shoulder (or lateral clearance), managed lanes, an outside shoulder, concrete barrier, and lateral clearance for the adjacent GP freeway lane, creating a general design envelope of 38 to 54-ft (16.3 to 18.8 m). Reducing the design envelope may be justified under special circumstances (e.g., right-of-way constraints, bridge crossing); however, such a reduction could adversely impact the safe and efficient operation of a facility.

Three different design scheme for concurrent-flow, managed-lanes are shown in **Figure 8**.

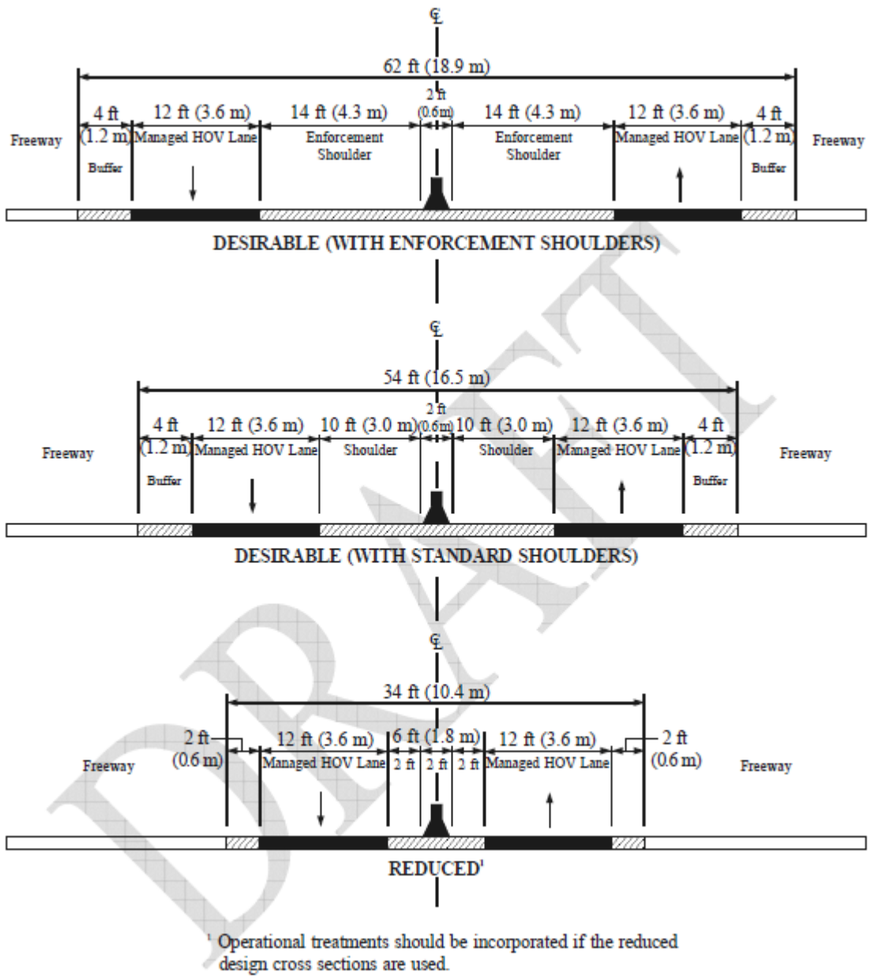
THOUGHTS FROM THE 2002 CALIFORNIA HOV SUMMIT (2002)

[Respectively: Jeff Lindley, Director, Office of Travel Management, FHWA; Tony Harris, Chief Deputy, Caltrans; Chuck Fuhs, Senior Project Manager, Parsons Brinckerhoff, Quade & Douglas, October 2002]

FHWA's position and policies require that, when communities desire to change HOV facilities, it is necessary that all techniques are employed to make the modified facilities a success. At the point a community decides to change HOV facilities, there is a federal process to be followed to permit review of any significant changes to the hours of operation and occupancy requirements.

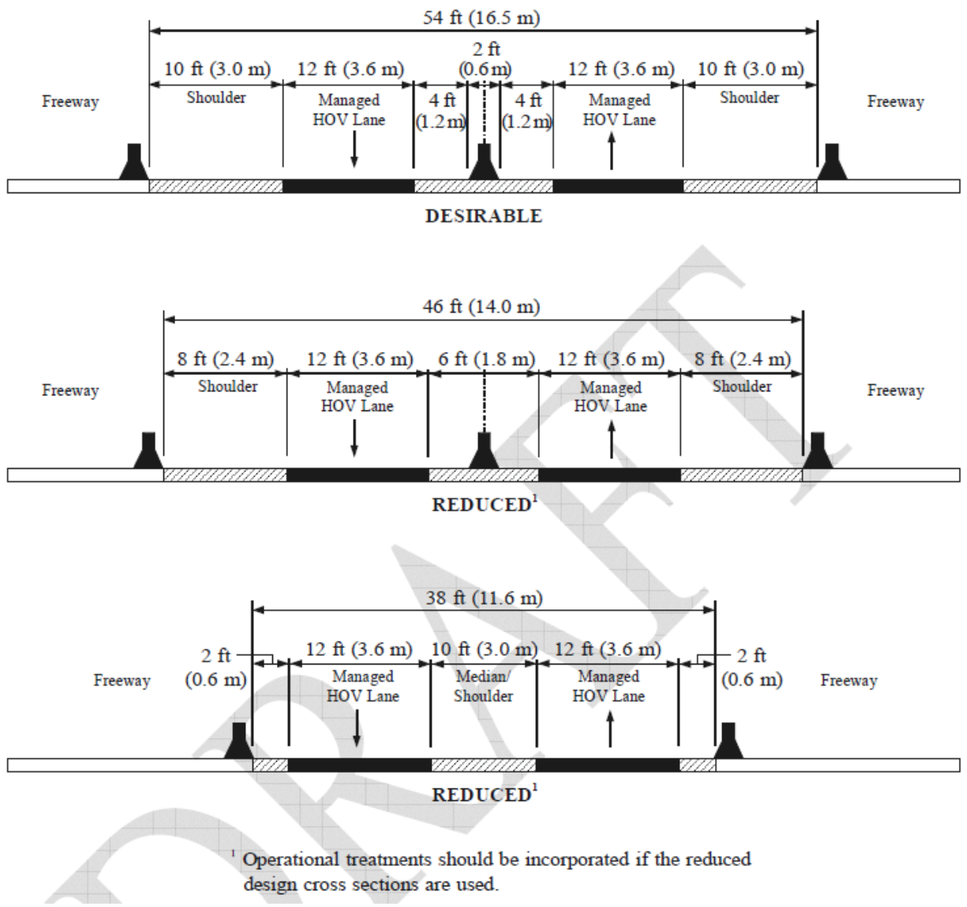
[41] It should be noted that hybrid versions of buffer-separated facilities, as described above, have been developed using flexible, reflective posts attached to the pavement or less permanent pylons; however, this type of treatment does not ensure exclusivity of the facility.

Figure 10 | Typical Cross-Sections Options for Concurrent-Flow, Managed-Lane Facilities



Source: Interim Manual for Managed Lanes, TxDOT; Adapted from Texas Transportation Institute, Parsons, Brinckerhoff, Quade, and Douglas, and Pacific Rim Resources. NCHRP Report 414: HOV Systems Manual. TRB, National Research Council, Washington, D.C., 1998.

Figure 11 | Typical Cross-Sections Options for Limited-Access, Managed-Lane Facilities



Source: Interim Manual for Managed Lanes, TxDOT; Adapted from Texas Transportation Institute, Parsons, Brinckerhoff, Quade, and Douglas, and Pacific Rim Resources. NCHRP Report 414: HOV Systems Manual. TRB, National Research Council, Washington, D.C., 1998.

DRAFT

The Caltrans representative pointed out that the safe operation of HOV facilities is important, as users need to count on reliability for trips. Maintenance of system reliability for users is the best motivator for travelers to use the HOV facilities.

Persons representing the Los Angeles Metropolitan Transit Authority (MTA) presented the findings of research performed to determine and understand HOV facilities use in Los Angeles County. An MTA consultant outlined nine concerns, one of which addressed safety. He noted that research was inconclusive, due to the fact that crashes occurring in the HOV lanes are not always identified as such, resulting in HOV lane crashes being comingled with the GP freeway lanes, or free-flow, lanes. The research team "…found no strong correlation to indicate that carpool lanes are unsafe."

Mobility Measures (2001)

[Chapter 24 – Mobility Measures, NYDOT Highway Design Manual, Revision 32, May 2001]

This Manual makes note of the following guidance provided in AASHTO's *Guide for the Design of High-occupancy Vehicle Facilities*. The HOV facility design that can be provided should allow for safe, efficient, and enforceable operation. With respect to enforcement, the Manual states:

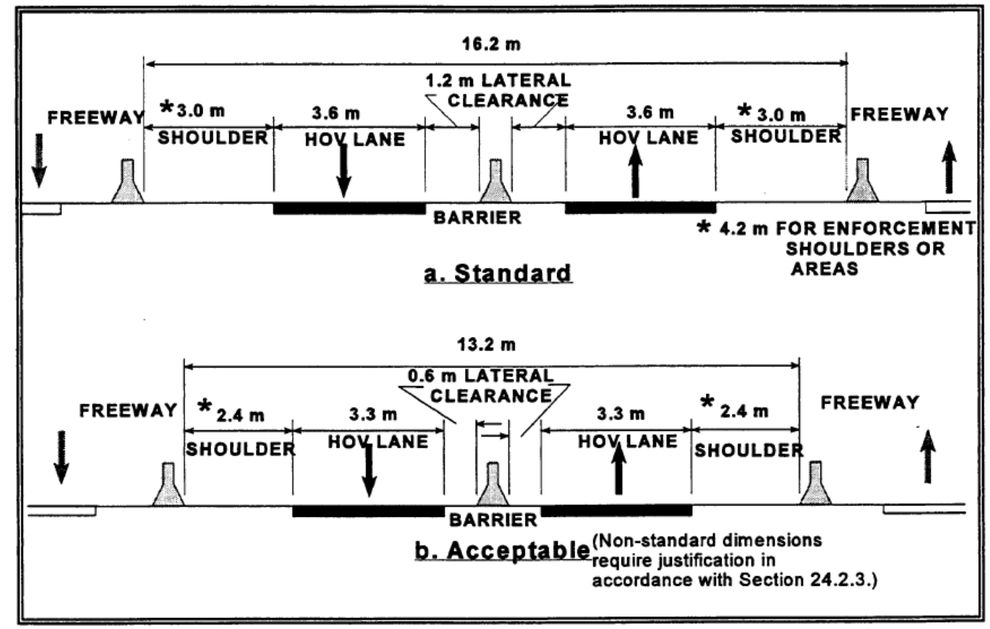
> *The absence or presence of certain roadway features can adversely affect the enforcement process as well as the safety and operational features of the facility. Physical problems may include lack of safe and easily accessible enforcement areas, absence of vantage points, lack of physical separation, and lack of passing capability for enforcement vehicles.*

Also, the Manual discusses the admission of commercial vehicles to HOV facilities. Although the potential for improving safety on the GP freeway lanes during peak periods is noted, the Manual also states the geometrics of HOV facilities may not be compatible with commercial truck movements. In addition, the weaving of large commercial trucks in the mixed-traffic of GP freeway lanes may be problematic. In any case, as noted above the intent of HOV facilities is to increase person throughput, and trucks do not contribute to this goal.

Regarding buffer-delimitation or buffer strips on the pavement to define a restricted area, i.e., HOV lane v. GP freeway lane, the width of a narrow buffer should be no greater than 1.2m (nominal 4 feet) or less than 0.3m (nominal 1 foot). A wide buffer should not be greater than 4.2m (nominal 14 feet) or less than 3.0m (nominal 10 feet). A narrow buffer should not exceed 1.2m and a wide buffer should not be less than 3.0m. Buffer widths within the 1.2m to 3.0m range are considered unsafe for drivers to use as a refuge.

The Manual notes that two-way, symmetrical, barrier-separated facilities provide safe operations, as they prevent traffic conflicts of HOV lane travel with the GP freeway traffic. It states that, "when dedicated access connections are provided, exclusive two-way flow lanes function as fully controlled lanes within a freeway and are considered the most desirable type of HOV treatment, albeit the most costly treatment." It is important to point out, the Manual emphasizes openings for access by emergency vehicles must be provided in the median barrier at reasonable intervals. Typical cross-sections for two-way, symmetrical, barrier-separated facilities are shown in **Figure 9**.

Figure 12 | Typical Cross-Sections for Barrier Separated Two-Way Flow HOV Lanes



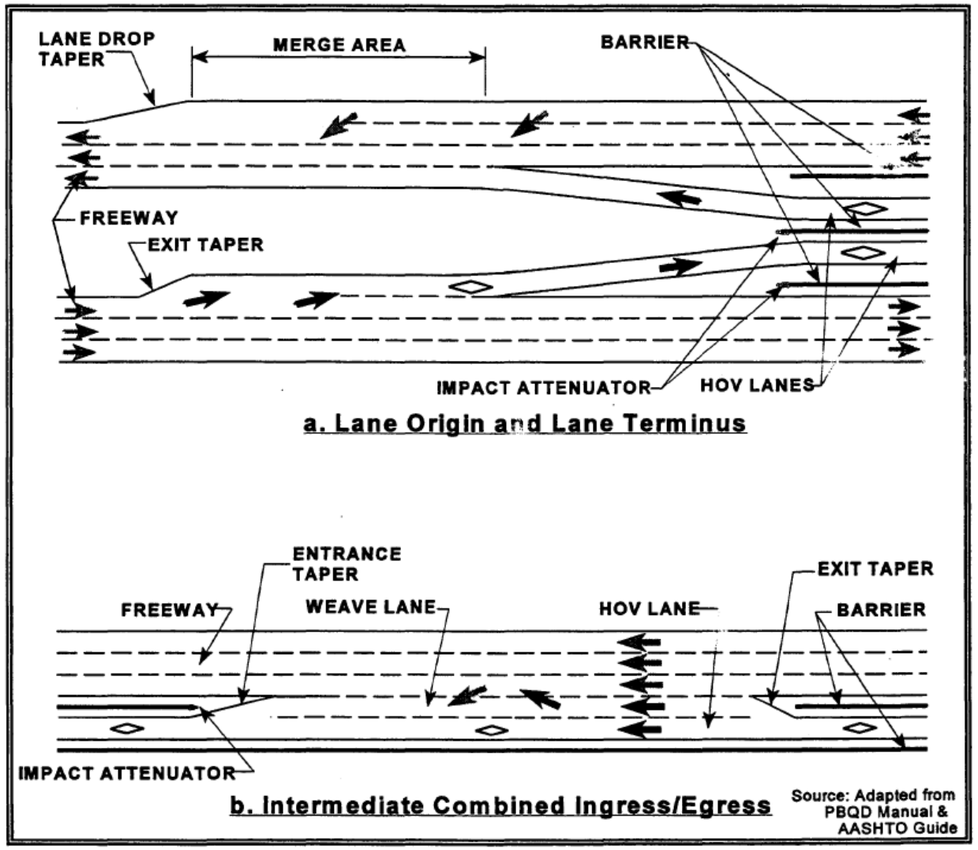
Ingress and egress is a critical challenge in the efficiency and safety of two-way, symmetrical, barrier-separated facilities. The Manual provides the following guidance for accommodating ingress and egress at the facility terminal points and at intermediate locations, in included. This guidance is cited below:

> *When conditions permit, intermediate ingress and egress should be provided at separate barrier opening locations to prevent conflicts between the associated weaves. Egress from the HOV lane should always precede ingress to the HOV lane to avoid congestion on the HOV lane. In addition, HOV egress should not be considered at the first access point downstream from the origin, and HOV ingress should not be considered at the last barrier opening upstream from the HOV lane termination. Each barrier opening should provide adequate distance for HOVs to weave into or out of the HOV lane. Special consideration should be given to the acceleration and deceleration characteristics of loaded buses, particularly if access ramps have significant grades. The weave distance should be calculated in accordance with TRB's Special Report 209 Highway Capacity Manual.*

When constraints prevent the installation of separate ingress and egress, they may be provided at the same location. If there is enough space available, a weave lane should be provided to allow the entering and leaving vehicles to make an orderly transition from one facility to the other. The opening length should generally range between 300 m and 450 m, as determined by a weave analysis in accordance with TRB Special Report 209, Highway Capacity Manual. Shorter distances may create a safety hazard by not providing adequate weave distance. Longer distances provide so much distance that the weave lane could be used as a passing lane by HOVs.

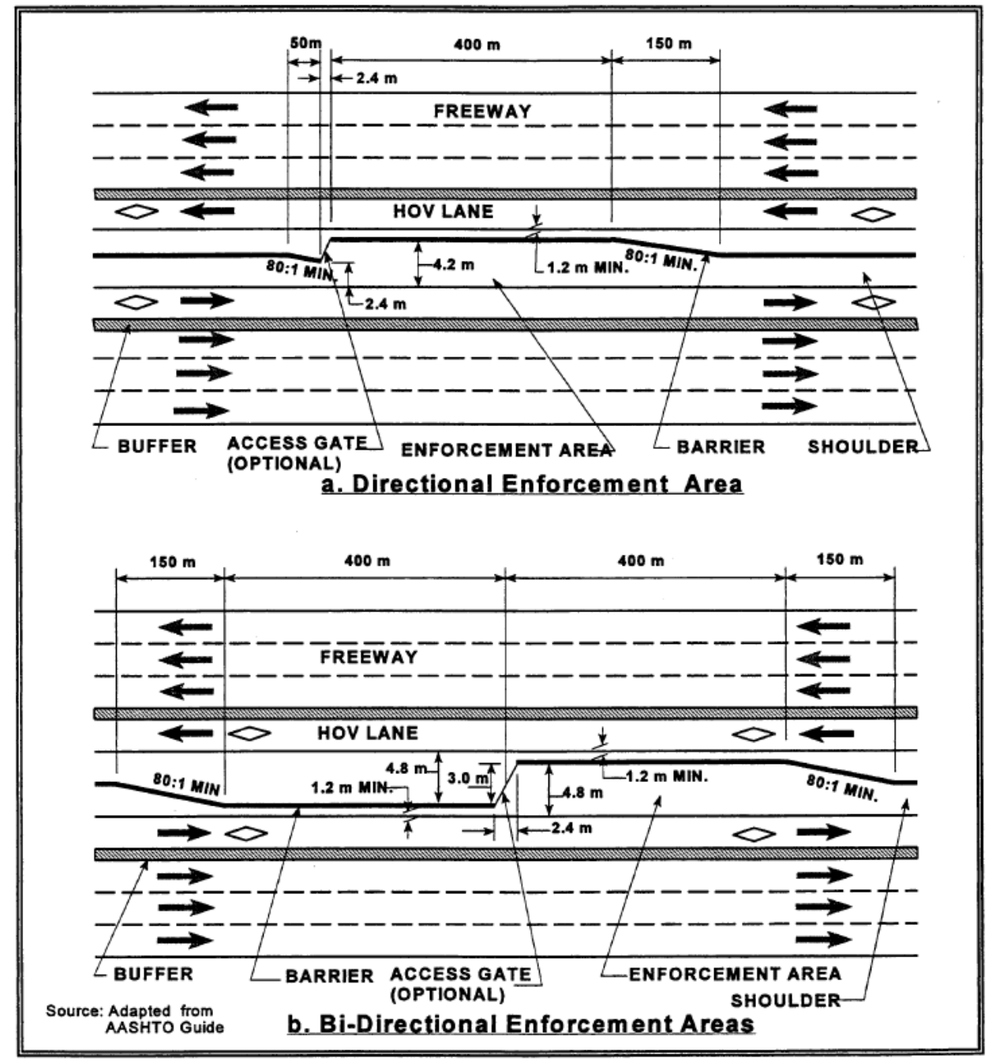
Figure 10 shows this graphically depicts the essence of this guidance.

Figure 13 | At-Grade Slip Ramps for Barrier-Separated Two-Way Flow HOV Lanes



Safety of operations associated with HOV/HOT managed-lane facilities generally includes accommodations for enforcement. Enforcement opportunities differ, depending on the width of the facility. For two-way, symmetrical, barrier-separated facilities with an inside shoulder, an enforcement area can be created by widening one shoulder into the other. Sufficient distance must be allocated to allow deceleration/acceleration of vehicles entering and existing the enforcement area. Two enforcement areas also can be paired. **Figure 11** shows two examples of enforcement areas for a two-way, symmetrical, barrier-separated facility. Buffer-separated, limited-access/intermediate-access lanes also may need to accommodate enforcement areas, as ingress and egress are facilitated at specified locations. Although it is possible, though not permissible to cross the buffer, these types of facilities effectively are barrier-separated with respect to vehicle operations.

Figure 14 | Median Enforcement Area for Medians 6.0 to 9.0 Wide



Non-separated, continuous, contiguous, concurrent-flow HOV/HOT managed-lane facilities provide greater ease of ingress/egress from/to the GP freeway lanes. However, enforcement is complicated by the lack of an enforcement area, unless an inside shoulder is sufficiently wide to accommodate stopped vehicles and pedestrian (primarily enforcement officers) movements. The principal safety issue associated with non-separated, continuous, contiguous, concurrent-flow HOV/HOT managed-lane facilities traffic is the risk of legal or illegal entry of low-speed vehicles from the GP freeway lanes, which may be congested, into the HOV lanes with greater free flow and, therefore, higher speed. Although contiguous lanes are separated by pavement striping, the minimal standard HOV facility with a 3.6m (nominal 12-f) lane and 3.0m (nominal 10-foot) inside (left shoulder) does not accommodate safe enforcement. If continuous enforcement or intermediate enforcement is too be maintained, then the inside shoulder needs to 4.2m (nominal 14 feet) wide.

OTHER REFERENCES RELATING TO HOV AND HOT FACILITY PLANNING, DESIGN, OPERATIONS, SAFETY, AND ENFORCEMENT

General

HOT Lanes, Cool Facts, Brochure, Federal Highway Administration, FHWA-HOP-12-027, March 23, 2012.

High Occupancy Vehicle Systems, CT-Caltrans, CA.gov at http://www.dot.ca.gov/trafficops/tm/hov.html.

Managed (HOV/HOT) Lanes, Mobility Investment Priorities, Texas Transportation Institute (TTI), May 16, 2013.

Safety-Related

A Comparative Safety Study of Limited Versus Continuous Access High Occupancy Vehicle (HOV) Facilities, California Path Program, Institute of Transportation Studies, University of California Berkeley, UCB-ITS-PRR-2009-22, ISSN 1055-1425, March 2009, Modified March 2010.

Establishing Crash Modification Factors and Their Use, Vikash V. Gayah and Eric T. Donnell, The Pennsylvania State University, Larson Transportation Institute (LTI 2015-02) for The Pennsylvania Department of Transportation, Bureau of Planning and Research, August 25, 2014.

Crash Prediction Method for Freeway Facilities with High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lanes, The Florida Department of Transportation Research Office, July 5, 2015.

Safety Implications of Managed Lane Cross Sectional Elements, Kay Fitzpatrick and Raul Avelar (Texas A&M Transportation Institute), Federal Highway Administration Office of Operations, FHWA-HOP-16-076, December 2016.

Safety Performance of High-Occupancy-Vehicle Facilities, "Evaluation of HOV Lane Configurations in California," Kitae Jang, et al, August 17, 2009; Originally printed in Transportation Research Record: Journal of the Transportation Research Board, No. 2099, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 132–140.

HOV and HOT Managed Lanes Pricing and Operations

Abstract: Impacts of High Occupancy Toll lane operations on High Occupancy Vehicle travelers, Guohui Zhang, et al, 13th International IEEE Conference on Intelligent Transportation Systems (ITSC), 2010, IEEE Document 5625273, September 19-22 2010.

HOT Lanes: A Better Way to Attack Urban Highway Congestion, Robert W. Poole Jr. and C. Kenneth Orski, in Regulation, Volume 23, No. 1, March 20, 2000.

HOT Lanes – An HOV Perspective, Prepared by King County Department of Transportation, November 25, 2003.

Impacts of Increasing Vehicle-Occupancy Requirements on HOV/HOT Lanes, A Preliminary Investigation, Joseph Rouse, Caltrans Traffic Operations, March 25, 2013.

Managed (HOV/HOT) Lanes – Adding Capacity from Strategies, Mobility Investment Priorities, Texas A&M Transportation Institute, May 16, 2013, retrieved at https://mobility.tamu.edu/mip/strategies.php, March 20, 2017.

Monitoring and Evaluating Managed Lane Facility Performance, Jodi L. Carson, Ph.D., P.E., Texas Transportation Institute for Texas Department of Transportation, FHWA/TX-06/0-4160-23, November 2005.

ATTACHMENT B

SITE CHARACTERISTICS CONSIDERATIONS FOR SEPARATION OF MANAGED LANES FROM GENERAL PURPOSE LANES

ATTACHMENT B

SITE CHARACTERISTICS CONSIDERATIONS FOR SEPARATION OF MANAGED LANES FROM GENERAL PURPOSE LANES

	Concrete Barrier	Buffer	Post
I. Lane & Shoulder Width			
1. Ideal lane and shoulder widths	Yes	Yes	Yes
2. Lane and shoulder widths less than ideal	Maybe – Must have room for the barrier itself. – Must have sufficient room in a managed lane delineated by barriers to allow incident bypass and clearing. – *Tunnel effect*: Users of managed lane may feel they have less room than they actually do; Level of Service may drop.	Maybe – Drivers will be less likely to maintain a high speed differential on a narrow lane; Level of Service may drop. – Unlawfully crossing boundary will be easier.	Maybe – Posts require a buffer of at least 2 ft. – Drivers will be less likely to maintain a high speed differential on a narrow lane; Level of Service may drop. – Unlawfully crossing boundary will be easier. – Posts may make users of managed lane feel like they have less room than they actually do; Level of Service may drop.
3. Shoulders available in managed lane	Yes	Yes	Yes
4. No or minimal shoulder available in managed lane	No – Motorists can be trapped behind an incident. – No room to safely avoid a disabled vehicle. – Emergency vehicles may not be able to reach an accident.	Maybe – No refuge for disabled vehicles.	Maybe – No refuge for disabled vehicles.
II. Traffic Considerations			
1. Uncongested main lanes	Yes	Yes	Yes
2. Congested main lanes	Yes + Physical barrier separates managed lane and main lanes, making higher speed differentials possible.	Maybe – Drivers may be uncomfortable with high speed differentials without physical separation. – Risk of drivers illegally swerving into managed lanes to pass slower traffic. ! A wide buffer may negate these effects.	Maybe – Drivers may be uncomfortable with high speed differentials without a more rigid separation ! A wide buffer may negate these effects.
3. Trucks allowed in managed lane	Yes + 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.	No – Having trucks in the fast-moving managed lanes without any physical separation from slower main lanes is unadvisable.	No – Having trucks in the fast-moving managed lanes without more substantial physical separation from slower main lanes is unadvisable. – Trucks often mow down posts, especially in restricted-width conditions.
4. Trucks in adjacent general-purpose lane	Yes + Provides protection for managed lane from adjacent, slow-moving trucks.	Maybe – No protection for managed lane from adjacent, slow-moving trucks.	Maybe – No protection for managed lane from adjacent, slow-moving trucks.
5. Buses/transit use managed lane	Yes ! Slow-moving buses may lower the Level of Service for the facility if a single-lane configuration is used.	Yes ! Slow moving buses may encourage people to weave in and out of managed lanes to overtake them.	Yes ! Slow-moving buses may lower the Level of Service for the facility if a single-lane configuration is used.
6. No buses on managed lane	Yes	Yes	Yes
III. Centerline Geometry			
1. Less than ideal horizontal curve radii	Maybe – 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.	Maybe – Drivers may feel uncomfortable making a sharp turn coupled with a high-speed differential.	Maybe – Drivers may feel uncomfortable making a sharp turn with a high-speed differential. – Posts may provide a distraction, which may increase stopping sight distance.
2. Ideal horizontal curve radii	Yes	Yes	Maybe – Use of posts on curves can be expected to increase maintenance costs due to vehicle impacts

Source: Table 2.1: Expert Panel Results, Site Characteristic Considerations, *Best Practices: Separation Devices between Toll Lanes and Free Lanes*, Texas Department of Transportation (TxDOT), FHWA/TX-07/0-5426-1, October 2006, Revised February 2007.

ATTACHMENT C

COMPARISON OF SEPARATION TREATMENTS

COMPARISON OF SEPARATION TREATMENTS

Separation Type		Rigid Barriers	Delineators	Pavement Markings
Safety	Pros	• Reduces General Purpose Lane and Express Lane side swipes • Express Lane traffic is separated from incidents in General Purpose Lanes	• Easier access for emergency vehicles since delineators can be driven over	• Easy access for emergency vehicles since there is no physical separation • Easy for Express Lanes traffic to vacate the lanes in case of an emergency or incident in the lanes
	Cons	• Access to lanes is restricted, therefore Incident Management response may take longer • With an incident in the Express Lanes, the impact to Express Lane traffic is high because of lane blockage • More difficult to vacate lanes in case of an emergency or incident	• Impacts to delineators can create roadway debris • Vehicles in the General Purpose Lanes are not physically separated from Express Lanes if an incident does occur	• More opportunity for General Purpose Lane and Express Lane side swipes • Vehicles in the General Purpose lanes are not physically separated from Express Lanes if an incident does occur
Right-of-Way	Pros	*None*	• No right of way typically needed for installation	• No right of way typically needed for installation
	Cons	• Right of way typically needed for access points installation	*None*	*None*
Cost	Pros	• Low maintenance • Allows for overhead sign structure uprights to be placed within barrier, which reduces sign structure spans	• Easy installation • Low installation cost	• Easy installation • Low installation cost
	Cons	• Higher cost for installation than other methods	• High maintenance costs due to frequent replacement of delineators that are hit by vehicles • No location for overhead sign structure uprights within area separating General Purpose Lane & Express Lane, which results in longer sign structure spans	• No location for overhead sign structure uprights within area separating General Purpose Lane & Express Lane, which results in longer sign structure spans
Express Lane Roadway Features and Operational Characteristics	Pros	• Allows for higher operating speeds in Concurrent Flow operations • Reduces toll avoidance • Better enforcement areas due to limited access points	• Provides some physical separation which can help reduce toll avoidance • Reduces illegal lane changes	• Easy to operate in mixed mode during non-peak times
	Cons	• When installed within existing roadway cross sections, design constraints may be involved • Mixed mode operations in non-peak times are not applicable • Special openings or devices may be needed for emergency vehicles during incident responses	• Hard to operate in mixed mode during non-peak times • Easily traversed • Hard to establish enforcement areas • Operating speeds may be lower than posted because of limited physical separation • Frequent maintenance on delineator replacements	• Illegal lane changes are not deterred • Hard to enforce illegal maneuvers and other infractions because enforcement areas are hard to establish • Operating speeds within the Express Lanes are typically lower than posted during congested times because no physical separation is present
Access Points	Pros	• Access points are controlled by physical separation making them easier to enforce and limits violators	• Easy adjustment of access points after initial installation • Access points are controlled by visual/soft separation limiting violators	• Easy adjustment of access points after initial installation
	Cons	• Possible flyovers or extra ramps required for General Purpose Lane left exits	• General Purpose Lane traffic may have to merge with Express Lane traffic for left exits	• General Purpose Lane traffic may have to merge with Express Lane traffic for left exits

ATTACHMENT D

PUBLIC PERCEPTION OF DIFFERENT BARRIER AND BUFFER SCHEMES

PUBLIC PERCEPTION OF DIFFERENT BARRIER AND BUFFER SCHEMES

System Separation Alternative	Perceived Pros	Perceived Cons
Pavement Markings (Buffer-separated)	▪ Inexpensive ▪ Familiarity to Atlanta residents ▪ Faster implementation possible ▪ Easy to remove if managed lanes system is unsuccessful ▪ Can vacate lane if necessary	▪ Easier to cheat this system ▪ Drivers can cut in and out of managed lanes
Concrete Barrier	▪ Reversible lanes concept is possible with this arrangement ▪ Feeling of safety when physically separated from the slower moving traffic in the general purpose lanes	▪ Some respondents feel this arrangement would exasperate their claustrophobia ▪ Fear of hitting the concrete barrier and damaging their vehicles induces some travelers to drive more slowly ▪ Trapped within the concrete barrier system in the event of an emergency
System Separation Alternative	Perceived Pros	Perceived Cons
Pylons	▪ Relatively inexpensive ▪ Provides a clear demarcation between lanes ▪ Travelers can drive over a pylon in an extreme emergency if necessary ▪ Easy to remove if managed lanes system is unsuccessful	▪ Frequent maintenance would be required for destroyed pylons
Grade Separation	▪ Perceived as efficient, especially for long trips ▪ The time and investment necessary elicited the response that this type of facility would best be suited as a HOT or toll system ▪ Feeling of safety when separated from slower moving traffic in the general purpose lanes	▪ Some respondents feel this arrangement would exasperate their claustrophobia and/or acrophobia ▪ Trapped within the system without a means to vacate in the event of an emergency ▪ Long construction times ▪ General disbelief that such a complex and expensive system would ever be implemented

Source: Table 1, Public Perception of Different Barrier and Buffer Schemes, in *Technical Memorandum 17B: Advantages and Disadvantages of Barrier versus Buffer Separated Managed Lanes,* Emerging Issues: Barrier versus Buffer Separated Managed Lanes, Atlanta Regional Manage Lane System Plan, Georgia Department of Transportation (GDOT), January 2010.