Role of High-Occupancy Vehicle Facilities in a Multimodal Transportation System

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High-occupancy vehicle (HOV) treatments are distinguished by their potential to serve demand management objectives while simultaneously increasing the productivity of existing highway facilities in terms of peak-period person-movement. In cities such as Boston, where rapid transit and commuter rail radial lines are used extensively, HOV facilities still may play a significant role in attracting markets that are not served by the rail system. A renewed interest in HOV options has emerged in the Boston area as an outgrowth of planning for the Central Artery–Third Harbor Tunnel. Environmentalists look to expansion of the project's HOV facilities at the regional level as a means of demand management, in the sense of reducing the potential growth in vehicular traffic attendant with a major increase in highway capacity. However, analysis of potential HOV lanes on the radial highways serving Boston indicates that frequently there are trade-offs with respect to mobility and demand management objectives. Moreover, forecasts show that person-movement capacity could be maximized in some cases with non-HOV transportation systems management measures. Right-of-way considerations also are critical in densely developed radial corridors, due to the immediate proximity of homes, commercial development, and, in some cases, environmentally sensitive areas such as wetlands. Because a variety of demand management measures can work for travel to and from the downtown area in Boston, HOV concepts should be evaluated as a component of an integrated regional strategy that optimizes the balance between mobility and demand management objectives.

The Central Artery–Third Harbor Tunnel project in Boston has been designed to incorporate a system of special facilities and preferential treatments for high-occupancy vehicles (HOVs). It is forecast that within the limited confines of the Central Artery/Tunnel (CA/T) project, this system will provide substantial advantages for HOV travel, with direct connections to the downtown street system, Logan Airport, and the rapid transit distribution system serving the downtown area. Because of the short distances covered by the HOV lanes, none of which exceeds 1 mi, travel time savings are forecast to range from only 1.5 to 6.5 min for the various movements provided. However, the system has been designed to connect at the southerly project limit with a much longer HOV line haul facility on the Southeast Expressway, which is being evaluated as a separate project by the Massachusetts Highway Department (MHD). If MHD decides to implement the Southeast Expressway HOV lane, which would be about 8 mi long, travel time savings would be far greater and the connections provided within the project limits would become increasingly important.

CA/T planners recently have analyzed alternative HOV concepts on each of the principal radial highways connecting to the project limits (see Figure 1), for the purpose of evaluating the project's HOV facilities within the broader context of a potential regional system. This analysis showed that exclusive regional HOV lanes would result in substantial travel time savings and increases in HOV use on each of the radial highways analyzed. As a result of implementing a regional system, HOV traffic volume within the project limits would increase to the point at which carpool eligibility requirements would need to be changed to preserve the travel time advantage in the HOV lanes.

The analysis also served to quantify the effects of alternative radial HOV lane configurations in terms of total vehicular volume and person-movement, as well as operating conditions in general-purpose lanes. The results showed that increased

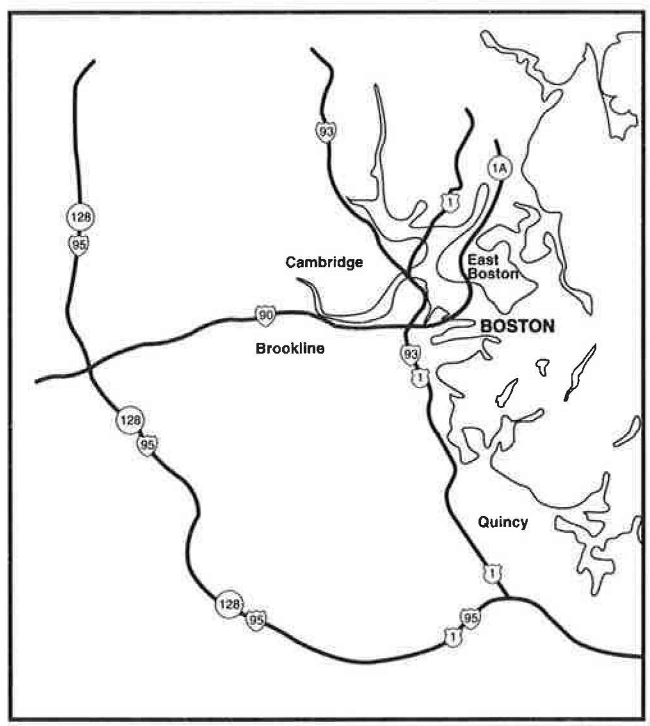

FIGURE 1 Boston metropolitan area highways, 2010.

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HOV use does not necessarily translate into commensurate reductions in the use of low-occupancy vehicles, and that frequently there are trade-offs between improvement in person-movement and demand management. In the Boston area, where radial HOV lanes are being advocated by environmental organizations as a mitigation measure to temper traffic volume growth, these trade-offs are a potential source of controversy with regard to HOV facility planning and design. This paper examines the relationship between the dual objectives of increasing person-movement and reducing vehicular traffic volumes, as it relates to HOV development in an area with practicable multimodal transportation options.

BACKGROUND

The CA/T project will address the need to improve both the capacity and safety of the existing Central Artery and, with a substantial expansion of highway capacity, provide better access to Logan Airport. The existing elevated Central Artery, which is the segment of I-93 that traverses downtown Boston, will be widened and placed in an underground alignment. A new four-lane cross-harbor tunnel on I-90 also will be provided as part of the project, thus doubling existing capacity.

The primary purpose of the HOV system incorporated in the CA/T project is to provide head-of-queue privileges at potential bottlenecks on I-93 and I-90 within the project limits, in a manner that facilitates further expansion of the system outside the boundaries of the project. Although the expansion of general-purpose capacity provided by the project will alleviate the severe traffic congestion experienced today on the Central Artery, there will remain several points of constrained capacity where delays will continue to be experienced in peak hours of travel, specifically at the entrances to the new tunnel on I-90 and at the southerly project limit on the Southeast Expressway (I-93). The CA/T HOV system will allow buses, carpools with two or more occupants, airport limousines, and taxis to bypass these operational bottlenecks, thus providing shorter and more reliable travel times. The system also will provide superior access to downtown Boston, the airport, and South Station, which is a major downtown rail and bus terminal that will serve in the future as a base for airport bus services.

The project's HOV elements will consist of dedicated HOV lanes, priority metering, and managed flow through mixed traffic. Specific facilities include exclusive northbound and southbound lanes on I-93, between the southerly project limit and downtown Boston; an eastbound collector-distributor roadway on I-90, most of which will be for the exclusive use of HOVs; priority metering at the eastbound and westbound I-90 tunnel portals and at the southbound merge with general-purpose traffic at the southerly project limit on I-93; and dedicated ramps between South Station and the HOV lanes (Figure 2). In addition, managed traffic flow downstream of the metering points will ensure uncongested traffic operations through the tunnel and on the roadways connecting to and from Logan Airport.

Each of the projects' HOV elements is forecast to produce measurable travel time savings for HOVs. During the p.m. peak hours in the design year 2010, travel times will be 6.5 min shorter for HOVs than general-purpose traffic between downtown Boston and the new tunnel. Peak-direction traffic volume is forecast to be about 1,000 vehicles for each of the HOV lanes during peak hours; the lanes will each carry between 4,000 and 5,000 peak-hour, peak-direction person trips, which is 2.5 to 4 times the number of people that will be carried in each of the general-purpose lanes. Overall, the system will be relatively small in scale but efficient: increasing person-movement, reducing HOV travel times, and providing the critical connections for HOV distribution in the downtown area.

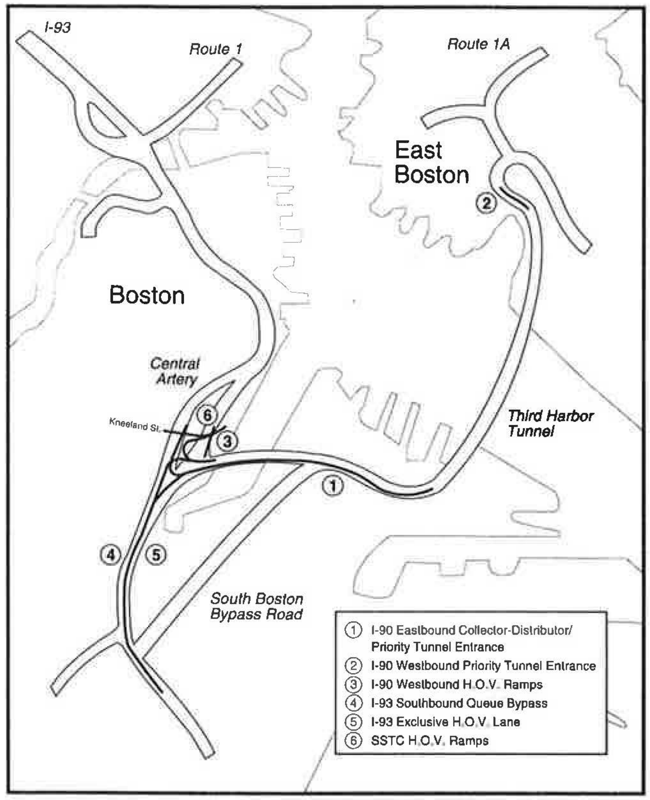

FIGURE 2 Proposed I-90–I-93 HOV system concept.

REGIONAL HOV SYSTEM PLANNING

CA/T Project in Relation to Radial HOV Facilities

From the outset, project planners envisaged a potential connection between the CA/T facilities and a radial HOV lane on the Southeast Expressway, which is the segment of I-93 to the south of the Central Artery. This radial line haul facility would extend about 8 mi, between the southerly CA/T project limit and the circumferential highway, Route 128. The expressway is congested because of high levels of traffic demand relative to available capacity; the right-of-way cannot be expanded appreciably because the highway borders developments and wetlands over much of its length. Because an HOV facility on the expressway would be much longer than the CA/T lanes, and congestion in the general-purpose lanes would be worse on the expressway than within the CA/T project limits (after project completion), potential HOV travel time savings and use of HOVs could be expected to increase substantially with the addition of an expressway HOV lane.

For a long time, the expressway has been regarded as a candidate for HOV facilities. HOV lanes were implemented in two separate trials during the 1970s, with unsuccessful results. A concurrent-flow lane created by borrowing a peak-direction general-purpose lane met with immediate and vociferous public opposition and was summarily terminated. A contraflow lane experiment was cancelled after an MHD employee working on the lane was struck and killed by a moving vehicle. The MHD plans feasibility studies to determine whether design concepts are possible that would avoid the pitfalls and hazards of these previous experiences.

The potential benefits of extending the project's HOV lanes are most apparent in the case of the Southeast Expressway, but planners have also considered the relationship of the CA/T HOV system to the other major radial highways serving downtown Boston: the Massachusetts Turnpike (I-90), which serves the corridor to the west of Boston; I-93 to the north of the Central Artery; and Route 1, which connects to I-93 immediately to the north of the Central Artery. This system-wide analysis approach was requested by FHWA to provide a sound basis for evaluating the HOV facilities planned as part of the CA/T project. The importance of this perspective has become increasingly evident, inasmuch as organizations concerned about the environmental impacts of the project have pressed for the development of extended radial HOV facilities. These facilities have been proposed to mitigate potential increases in vehicular traffic volumes that environmentalists fear will result from the expansion of highway capacity made possible by the CA/T project.

The environmental argument advanced in support of radial HOV lanes in the Boston metropolitan area has focused exclusively on their potential role in demand management. Customarily it is considered good planning and engineering practice to evaluate HOV concepts according to a range of criteria related to both HOV and general-purpose traffic performance (*1*), but the priority for environmentally minded HOV advocates in Boston has been to shift single-occupant automobile drivers to buses and carpools and to give much less consideration to the effects on general-purpose traffic operations. A memorandum of understanding between several of the state transportation agencies and one of Boston's leading environmental advocacy groups exemplifies this orientation. Among other demand management measures, this agreement mandates the implementation of several radial HOV facilities, based solely on their potential benefits for HOVs. In fact, it is stipulated that the new HOV lanes be created on the Massachusetts Turnpike and I-93 north of the city through means other than lane addition. Taking away peak-direction general-purpose lanes implicitly is acceptable within the terms of this agreement, even though this practice may be detrimental to overall traffic operations and proved to be a failure when previously attempted in Boston.

Evaluation of Radial HOV Options

A range of potential HOV concepts has been evaluated to address regional-level issues that could affect the HOV system within the project limits, as well as broader demand management objectives associated with environmental mitigation. In general terms, the concepts tested consisted of the following: concurrent-flow (i.e., same direction) lanes, created by taking away a lane from peak-direction general-purpose traffic; barrier-separated contraflow lanes, created by taking away a lane from off-peak or reverse-direction traffic, assumed to be safe for carpools and vanpools as well as buses; and reversible HOV lanes, created by adding one or two HOV lanes to the existing general-purpose lanes. The analysis was based on year 2010 forecasts of HOV traffic volumes or demand as well as the impacts of alternative concepts on operating speeds in both HOV and general-purpose travel lanes.

These forecasts were generated by the Central Transportation Planning Staff (CTPS) which serves the Boston Metropolitan Planning Organization. The method used to develop the forecasts involved adjustments of existing model networks to incorporate HOV alternatives, assignment of traffic using the Urban Transportation Planning System (UTPS) and pivot-point estimation techniques to relate computer-forecasted travel time differences among the alternatives to vehicle occupancy rates. The results are summarized in Tables 1 and 2. The pivot-point analysis provided estimates of vehicle occupancy by traffic zone, based on empirical relationships between variations in travel time savings and average vehicle occupancy. This methodology was based on the earlier Bolling-Anacostia forecasting model and a model developed by the Metropolitan Washington Council of Governments. A noteworthy characteristic of the forecasting procedure is that the total volume of network vehicle trips is held constant across the alternatives under study. Variations in vehicle occupancy rates correspond to changes in the total number of person trips.

Among the four radial highways studied, potential HOV benefits would be greatest on the Southeast Expressway—which is to be expected, given the magnitude of congestion forecast to occur on that highway. Compared to a year 2010 baseline condition in which no HOV lanes are provided, HOV travel time savings would be about 16 min for all of the expressway concepts analyzed. In comparison, HOV travel time savings on the other radial highways would range from 5 to 9 min. Substantial increases in HOV use would result on all the highways, most particularly on the Southeast Expressway, on which approximately 1,500 HOVs and 5,200 HOV person-trips would be added during the 3-hr a.m. peak period, with HOV eligibility defined as 3 or more occupants per vehicle. Analysis of the impacts on HOV usage within the project limits shows that the eligibility requirement would need to be raised to 3-or-more occupancy, if a radial HOV lane were provided on the Southeast Expressway, because HOV volumes on the CA/T HOV lanes would rise dramatically. With a 3-or-more occupancy eligibility requirement, the peak-hour volume on I-93 north within the project limits would slightly exceed the standard maximum threshold of 1,500 vehicles.

The forecast data provide some revealing comparisons of the effects of different HOV concepts. As might be expected, the concurrent-flow take-away lane options would result in the degradation of traffic operations in the general-purpose lanes, with HOV eligibility defined as 3 or more occupants per vehicle. General-purpose speeds on the Southeast Expressway would decline by an average of 3 mph during the 3-hr a.m. peak period, resulting in an average increase in travel time of 5 min, or 23 percent, over the length of the

TABLE 1 Impacts of HOV Options on 3-hr A.M. Period Traffic Operations, Year 2010 (3+ Occupancy HOV Eligibility)

ROADWAY	INBOUND				OUTBOUND	
	SPEED (MPH)		TRAVEL TIME (MIN)		GENERAL PURPOSE	
	HOV	MIXED FLOW	HOV	MIXED FLOW	SPEED (MPH)	TRAVEL TIME (MIN)
SOUTHEAST EXPRESSWAY						
Baseline	19	19	25	25	52	9
Concurrent	54	16	9	30	53	8
Contraflow	56	21	8	22	45	10
Added Reversible HOV Lane	55	21	9	22	55	8
Reversible Mixed Flow	30	30	16	16	46	10
MASSACHUSETTS TURNPIKE						
Baseline	27	27	23	23	54	12
Concurrent	49	22	13	29	54	12
Contraflow	44	28	14	22	39	16
Added HOV Lane	44	28	14	22	54	12
I−93						
Baseline	31	31	16	16	51	10
Concurrent	57	28	8	18	50	10
Contraflow	57	33	9	15	34	15
Added HOV Lane	57	33	9	15	51	10
ROUTE 1						
Baseline	29	29	19	19	49	11
Concurrent	39	26	15	22	49	11
Contraflow	49	31	12	18	49	12
Added HOV Lane	35	30	16	19	49	11

TABLE 2 Impacts of HOV Options on 3-hr A.M. Peak Period, Peak Direction Traffic Volumes, Year 2010 (3+ Occupant HOV Eligibility)

ROADWAY	VEHICLE TRIPS		PERSON TRIPS	VOR (1)
	HOV	TOTAL		
SOUTHEAST EXPRESSWAY				
Baseline	1360	25340	31870	1.26
Concurrent Flow	2910	22350	32180	1.44
Contraflow	2760	27910	38110	1.37
Added Reversible HOV Lane	2750	26920	36960	1.37
Reversible Mixed Flow Lanes	1920	32370	41150	1.27
MASSACHUSETTS TURNPIKE				
Baseline	1150	18520	23670	1.28
Concurrent Flow	1790	17060	23540	1.38
Contraflow	1520	18910	24990	1.32
Added HOV Lane	1520	18900	24980	1.32
I−93				
Baseline	1490	19920	26060	1.31
Concurrent Flow	2600	14690	22790	1.55
Contraflow	2090	19920	27490	1.38
Added HOV Lane	2080	19890	27430	1.38
ROUTE 1 (2)				
Baseline	1920	11900	14400	1.21
Concurrent Flow	2640	12140	15580	1.28
Contraflow	2960	12540	16400	1.31
Added HOV Lane	2290	11910	14890	1.32

(1) VOR= VEHICLE OCCUPANCY RATE
(2) 2+ OCCUPANT HOV ELIGIBILITY ON ROUTE 1

expressway. In contrast, the contraflow and reversible-added concepts would result in a 2-mph improvement in general-purpose traffic speeds, due to the reduction in per-lane volumes associated with the addition of a peak-direction lane, which would translate into a 3-min decrease in travel time.

The impact of the take-away lane versus the contraflow and added-lane concepts is even more striking in terms of person-movement, which is a critical—if not overriding—measure of overall performance. On the Southeast Expressway, the concurrent-flow take-away lane is forecast to produce a negligible increase in the total number of person trips carried over the entire 3-hr a.m. peak period. In contrast, the contraflow and added-reversible lanes would result in a net peak-period increase of 5,000 to 6,000 person trips. On I-93 and the Massachusetts Turnpike, the take-away concurrent-flow lane concepts are forecast to produce losses in peak-period person-movement, whereas the contraflow and reversible-added concepts would add 1,300 to 1,400 person trips. On the basis of the differences between the options in terms of this indicator, there is little justification for concurrent-flow take-away lane HOV concepts.

Because person-movement is so critical, it is noteworthy that the number of peak-period person trips could be maximized on the Southeast Expressway with a non-HOV transportation systems management (TSM) alternative. The TSM concept consists of the conversion of one northbound and one southbound general-purpose lane into two reversible lanes that would be open to all traffic. The net effect would be to add one mixed-flow lane to the peak direction in both the morning and evening peak periods, yielding a total of five peak-direction lanes. The impact of this concept, in terms of person-movement, was forecast to be an increase of 9,000 peak-period person trips.

Another important benefit of the non-HOV reversible-lane concept would be its effect on operating speeds. All of the concepts that involve expansion of peak-direction capacity (i.e., contraflow HOV, reversible-added HOV, and reversible-added mixed-traffic) would result in some improvement in operating speeds not only for HOVs but for general-purpose traffic as well. All the HOV concepts would provide for HOV travel at about the legal limit of 55 mph. The HOV concepts created by adding peak-direction lanes would also result in a small improvement in general-purpose operating speeds, as described previously. In contrast, the non-HOV reversible-lane concept would increase speeds in all peak-direction lanes to 30 mph, compared with the forecast baseline speed of 19 mph. However, an HOV lane may be superior to a mixed-traffic reversible concept if mixed-flow volumes increase substantially in relation to available capacity. In that case, an HOV lane would provide for greater potential person-movement.

Of course, person-movement and speed are not the sole criteria by which transportation measures are judged. HOV priority is distinguished by its potential to serve the dual objectives of increasing person-movement on highway facilities and reducing the use of low-occupancy vehicles. In terms of demand management, the relative benefits of HOV treatments are illustrated by the forecasts of vehicle occupancy rates (VORs) and vehicular traffic volumes for the various alternatives analyzed. On the Southeast Expressway, the 2010 baseline VOR is forecast to be 1.25 occupants per vehicle. The 3-or-more occupant concurrent-flow take-away lane HOV concept would result in the greatest increase in VOR, to 1.44. As described previously, this increase in vehicle occupancy would be accomplished at substantial cost: degradation of traffic conditions in the already-congested general-purpose lanes and negligible improvement in person-movement. The substantial improvement in VOR is attributable in part to a decrease in the total number of vehicles that would be carried on the highway, reflecting a reduction of about 4,500 low-occupancy vehicle trips during the a.m. peak period without a commensurate increase in HOV trips.

The other HOV concepts on the expressway would result in VOR of approximately 1.37, which represents an increase of about 10 percent over the baseline condition. In contrast, the VOR for the non-HOV reversible-lane concept would be only 1.27, which is essentially equal to the baseline VOR. Overall, the forecast data indicate that the contraflow and reversible-added HOV lanes would strike a balance between the objectives of reducing the volume of vehicular traffic and increasing the number of person trips accommodated during peak periods.

Nevertheless, the analysis results suggest some further questions about the net impact of the various alternatives with respect to areawide, as opposed to facility-specific, transportation objectives. The contraflow and added-lane HOV concepts are forecast to balance mobility and demand management objectives on an individual highway, but an optimal balance for the area served by the highway could be achieved through alternative strategies that involve different modes, such as rail transit.

HOVs and Demand Management

In particular, the forecasts of impacts on the distribution of vehicular traffic volumes indicate the need for a broader analysis of HOV facilities in terms of demand management objectives. It is reasonable to expect that an HOV lane and a parallel rail line might compete for users and that some new HOV users would be diverted from rail transit rather than from single-occupancy vehicles. The forecast data illustrate the potential magnitude of such impacts. The contraflow and added-HOV lane concepts would produce a substantial net increase in the number of low-occupancy vehicles carried on the Southeast Expressway during the a.m. peak period. Although much smaller in magnitude, effects of the same type are forecast for the turnpike and Route 1.

Because the forecasting models used in this analysis do not indicate the modes from which new HOV person trips would be drawn, the results do not provide conclusive evidence of the extent to which HOV users are diverted from rail transit. Even when an increase in vehicular traffic volumes is not forecast in association with HOV facilities, as on I-93, the likelihood is that in the Boston metropolitan area at least some of the increase in HOV use would be at the expense of rail transit ridership. However, such cases probably would mean not a net increase in vehicular travel on an areawide or regional basis, but instead a neutral shift from one high-occupancy mode to another. The increase in total vehicle trips on the Southeast Expressway, in particular, and to a lesser extent on the turnpike and Route 1, raises the prospect that a net increase in the use of automobiles could occur on an areawide basis. Not only total vehicular traffic volume but also the number of low-occupancy vehicle trips are forecast to increase on the expressway if contraflow or reversible-added HOV lanes are implemented.

The implications of the rail diversion factor can be illustrated in terms of VOR. The 1.37 VOR forecast to result from the contraflow HOV lane would decline to 1.29 if just one-third of the forecast increase in peak-period person trips on the expressway is discounted as diversion from rail transit. This magnitude of diversion is plausible and possibly conservative, considering that a rapid transit line parallels the highway and that a radial commuter rail line is scheduled to be in operation by the middle of this decade in the same corridor to serve longer trips. The lower VOR is an indicator of a substantial reduction in benefit with respect to demand management. If half of the increase in person trips results from diversion away from the rail system, and therefore is discounted, the VOR would decline to the baseline level of 1.25. In this case, there may be no net benefit in terms of demand management.

Even if demand management benefits turn out to be less than initially supposed, however, the contraflow and added-lane HOV concepts would still result in a substantial improvement in person-movement. Improved productivity, coupled with some reduction in vehicular travel and improvement in traffic operations, still makes a strong argument in favor of HOV facilities, assuming that they are feasible to design and operate. In the densely developed Boston metropolitan area, however, HOV options tend to be constrained by lack of right-of-way. This is particularly true of the Southeast Expressway. A reversible-added lane may require widening of the roadway by about 20 ft, which probably is not feasible because of the proximity of residential and commercial development in some locations and the likelihood of impacts to wetland areas elsewhere. Construction of the HOV lane in an elevated viaduct is a possible alternative that would entail visual and noise impacts as well as substantial cost. Contraflow is yet another possibility, but highway widening would be required and operating costs could be excessive. Moreover, an analysis conducted by CTPS indicated that reverse-direction general-purpose traffic flow would be impaired by the loss of a travel lane, taking into account projections of future traffic growth by the year 2010.

The physical constraints associated with retrofitting an urban highway with HOV lanes can be significant. For this reason, options that can be accommodated within the existing right-of-way deserve serious consideration. It may be possible to implement the non-HOV reversible lane concept without substantial right-of-way expansion on the Southeast Expressway. This option clearly would not serve demand management objectives—it might actually encourage increased use of automobiles—but its benefits in terms of improved highway operations and person-movement could outweigh its liabilities. To the extent that demand management is motivated by constraints on new highway construction, increasing the productivity of existing highway facilities may effectively serve the same purpose, even if traffic volumes increase.

The goal of environmental protection definitely would not be addressed by increasing the use of automobiles. Nevertheless, because vehicular exhaust emissions are reduced when traffic congestion is alleviated, some increase in traffic volume may be tolerable if traffic operating conditions are improved substantially. They apparently would be improved if the Southeast Expressway, and possibly other highways in Boston and other metropolitan areas, were retrofitted with reversible mixed-flow lanes. This concept appears to warrant consideration in conjunction with HOV planning in some areas.

The areas in which this concept might be most appropriate include Boston and other cities where the objective of reducing vehicular traffic may be addressed through various means, including increased use of bus and rail public transportation. One of the principal incentives to use public transportation downtown is the scarcity and high price of parking, which is reinforced in Boston through public policy, as manifested in controls on the off-street parking supply. Further improvements in the existing public transportation system, such as reducing headways and increasing the supply of commuter parking, could temper growth in vehicular traffic to the core of the metropolitan area. Congestion-pricing and increased gasoline and vehicle taxes are highway-oriented traffic management measures that could be disincentives to driving. All of these measures could be implemented as part of a regional strategy that may or may not include HOV facilities. In many urban areas that cannot be served adequately by rail transit, however, HOV lanes are likely to remain among the more powerful demand management tools.

CONCLUSION

The development of HOV forecasting models, although still in a preliminary stage, has provided the ability to predict a broad range of HOV facility operating characteristics, including demand, impacts on speeds for both HOVs and general-purpose traffic, and changes in person trips as well as vehicular traffic volumes. In the Boston metropolitan area, this forecasting ability has been used to evaluate potential HOV facilities, including those planned from a regionwide systems perspective as part of the CA/T project.

The results of this analysis show that future HOV demand is strong on the radial highways serving Boston and that the function of the project's HOV connections would become increasingly important in the context of a regionwide system.

The analysis also serves to underscore the importance of a multimodal planning framework in cities such as Boston where rail service is frequently an alternative to HOV facilities. The forecasts indicate that total peak-period vehicle trips would increase on some highways as a result of implementing HOV facilities through lane addition. This raises the issue of how many of these trips would be drawn from alternative highway routes versus parallel rail lines. Another result that appears to merit further investigation is the superior performance of a non-HOV reversible-lane concept, in terms of its impacts on operating speeds in all lanes as well as total person-movement.

Some of the HOV concepts studied did appear to combine successfully the benefits of increased automobile-occupancy and person-movement and therefore may prove to be optimal