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Joy Dahlgren

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HIGH OCCUPANCY VEHICLE LANES: NOT ALWAYS MORE EFFECTIVE THAN GENERAL PURPOSE LANES

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Abstract—The success of a high occupancy vehicle lane in motivating people to shift to carpools and buses depends on maintaining a travel time differential between it and the adjacent general purpose lanes. This differential, in turn, depends on the level of continuing delay on the general purpose lanes. Therefore, it is clear that a high occupancy vehicle lane that will motivate people to shift to high occupancy vehicles will not eliminate congestion. Consequently, it is not clear that constructing a high occupancy vehicle lane will necessarily reduce delay more than construction of a general purpose lane. The objective of this research is to determine the circumstances in which this would be the case. The hypothesis is that such circumstances would be quite limited, and this proves to be the case. The intended benefits of high occupancy lanes are defined as reduced person-delay and reduced emissions. A model is developed to calculate these benefits for four alternatives: add a high occupancy vehicle lane, add a general purpose lane, convert an existing lane to a high occupancy vehicle lane, and do nothing. The model takes into account the initial conditions, the dynamic nature of the travel time differential between the high occupancy vehicle lane and other lanes, and the uncertainty regarding the extent to which people will shift modes. It combines queueing theory and mode choice theory and provides a robust method for comparing alternatives using a small amount of easily observed data. Application of the model in typical situations shows that with initial delays on the order of 15 min or more, adding a high occupancy vehicle lane would provide substantial reductions in delay and some reduction in emissions. However, in a wide range of such situations, adding a general purpose lane would be even more effective. Only if the initial delay is long and the initial proportion of high occupancy vehicles falls in a rather narrow range, would an added high occupancy vehicle lane be more effective. The proportion of high occupancy vehicles must be such that it allows good utilization of the high occupancy vehicle lane while maintaining a sufficient travel time differential to motivate a shift to buses or carpools. Adding a high occupancy vehicle lane to a three lane freeway will be more effective than adding a general purpose lane only if the initial maximum delay is on the order of 35 min or more and the proportion of high occupancy vehicles is on the order of 20%. Federal policies encourage construction of high occupancy vehicle lanes and restrict funding for general purpose lanes in areas that have not attained air quality standards. The findings of this research suggest a need to reconsider these policies. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: high occupancy vehicle, high occupancy vehicle lane, carpool lane

1. INTRODUCTION

The benefits of constructing a high occupancy vehicle (HOV) lane are obvious: by providing an incentive for people to shift from automobiles with one or two occupants to carpools or buses, the HOV lane reduces vehicle-trips, thereby reducing congestion and air pollution. Less obvious is the fact that in many situations the benefits would be as great or greater if the new lane were a general purpose lane instead.

The reasons for this are simple. The unique benefits of an HOV lane as compared to a general purpose lane—that it motivates a shift to HOVs and gives priority at the bottleneck to HOVs—do not arise unless delay continues on the general purpose lane. If delay is eliminated when the HOV lane is constructed, there will be no incentive to shift to an HOV. But even if delay continues on the general purpose lanes, two factors limit the extent of the mode shift.

(a) In-vehicle travel time has been found to have a weak effect on mode choice. Small (1977) found a minute of out-of-vehicle wait time to be valued at almost 10 minutes of in-vehicle time and a transfer, at 13·6 minutes of in-vehicle time. Kollo (1986), in updating the travel model for the Metropolitan Transportation Commission in the San Francisco Bay Area, found even less sensitivity to in-vehicle travel time than Small.

(b) The motivation to shift mode depends on the differential in travel times on the HOV lane and the other freeway lanes. As people shift to HOVs, this differential is eroded. Therefore, regardless of how much overall traffic increases, there is an upper limit on the travel time differential and the proportion of people who will be motivated to shift to an HOV lane. Furthermore, if the initial proportion of HOVs is greater than the proportion of capacity that will be devoted to HOVs after the HOV lane is added, the HOV lane will be as congested as the general purpose lanes and will offer no travel time advantage.

The key question is under what circumstances does constructing an HOV lane result in less delay and lower emissions than constructing a general purpose lane? To answer this question, the effects of constructing either type of lane are identified and a model to compare the benefits of the each is developed

Constructing an HOV lane has several interrelated effects (Fig 1) The most significant effect is the shift of current HOVs to the HOV lane This shift reduces delay on the general purpose lanes, perhaps eliminating it altogether If delay remains on the general purpose lanes, some people shift to HOVs, further reducing delay on the general purpose lanes The reduced delay for both HOVs and non-HOVs (hereafter referred to as LOVs—low occupancy vehicles) motivates some people traveling on the shoulders of the peak to shift their trip to the peak It also motivates people to shift from other routes that are now slower. It may induce trips by people who previously did not travel because of the delay In the long run, the reduced delay may result in more development and trips than would have otherwise been the case. These last four effects offset the original reductions in delay. Except for the shift to HOVs, constructing a general purpose lane has the same types of effects, although the effects have different magnitudes The reduction in number of trips and vehicle-miles resulting from the shift to HOVs reduces emissions of the three commonly measured pollutants nitrogen oxides, hydrocarbons, and carbon monoxide. The reduction in delay further reduces emissions of hydrocarbons and carbon monoxide, which are roughly proportional to vehicle-hours (Seitz, 1989), (USEPA, 1992). Because the reduction in delay affects thousands of vehicles, while the number of vehicles removed from the road is relatively small, the delay reduction generally has the more powerful effect on overall emissions. Therefore, although constructing a general purpose lane does not reduce the number of vehicle-trips, if it is more effective in reducing delay, it generally will also be more effective in reducing overall emissions.

Analyses of HOV lanes often concentrate on the reduction in HOV delay, the shift from LOV to HOV, and the effect of this shift on emissions and person-delay. Thus they ignore the other, generally greater, effects on delay to LOVs and emissions from LOVs.

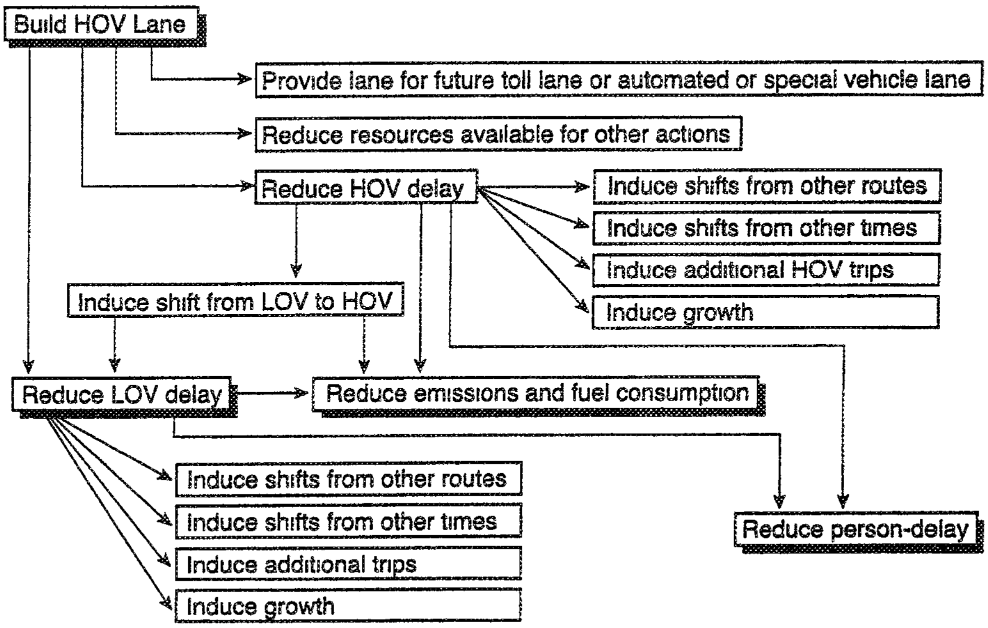

Fig 1 The effects of constructing an HOV Lane

2 A MODEL FOR COMPARING THE BENEFITS OF HOV LANES AND GENERAL PURPOSE LANES

Current planning methods for HOV lanes generally use static transportation planning models which provide only peak hour travel times and volumes. Translation of these measures into vehicle-delay and vehicle-trips requires assumptions that are highly uncertain, such as the distribution of trips, mode shift, and vehicle occupancy over time. An exception is the FREQ model, which has been used in the evaluations of the Houston HOV lanes It is dynamic and can model delay for freeways with or without HOV lanes or a parallel arterial. However, its extensive data requirements make it expensive to use. A new HOV lane planning method developed by Dowling Associates (1996) is less data intensive and also accounts for the dynamic nature of travel demand but does not account for the continuous interaction between the proportion of HOVs and the travel time differential between the general purpose and HOV lanes.

The model used in this research bases estimates of the proportion of people using HOVs on the time differential between the HOV lane and other lanes, which is constantly changing The model is easy to use and transparent so that the effects of uncertain inputs can be easily examined Because it has limited data requirements, available resources for collecting and verifying data can be concentrated on less data A key feature of the model is that, while it is very simple and does not include all of the effects of adding a lane, it can be shown that not including these effects does not change the performance ranking of the two types of lane For example, neither this model nor FREQ include the effects of changes in trip start time While such changes strongly affect travel patterns and delay, they are not important in comparing the effectiveness of an HOV lane versus a general purpose lane because, as will be discussed later, whichever lane yielded the greatest benefits before the shift in trip starting times will also yield the greatest benefits after the shift. The same is true of the effects of route shifts and induced trips. These effects are discussed in more detail in the Appendix

2 1 *Estimating delay*

Consider an idealized freeway segment as shown in Fig 2 There is a bottleneck at the downstream end and the neck is long and uniform, contains no entry or exit points, and extends beyond the area subject to congestion. The queue builds up and dissipates during the peak period as shown in the lower section of Fig 2 Vehicles arrive at a constant rate until the time of the maximum queue and then arrive at a lower constant rate until the queue is dissipated An idealized queue can be constructed from the following information.

(a) the length of the congested period
(b) the maximum delay (maximum travel time minus free flow travel time)
(c) the time at which the maximum delay occurs
(d) the freeway capacity

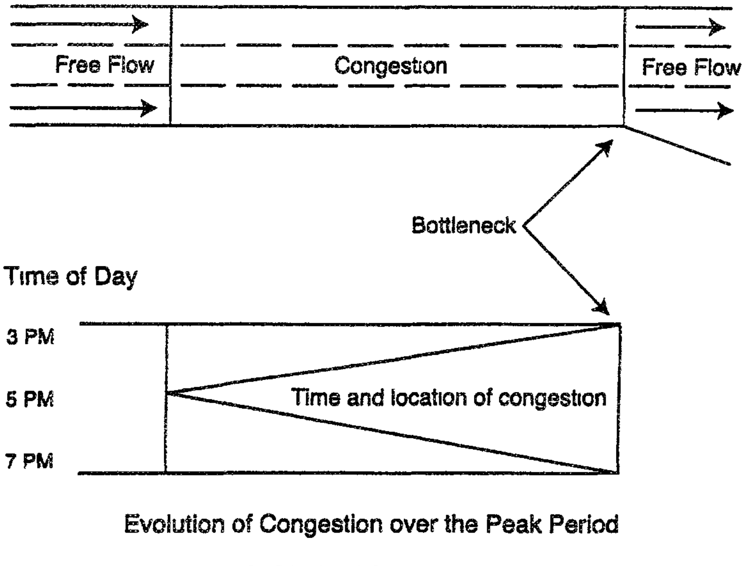

Fig 2. Idealized freeway segment

The queue can be represented as in Fig 3 The congested period extends from 0 to t_E, with the maximum delay occurring at $t^{\max}$ The cumulative number of vehicles attempting to pass through the bottleneck at time t is $A(t)$ and the number actually passing through is $D(t) = ct$, where c is the capacity of the bottleneck per unit of time The number waiting to pass through at time t is

$$Q(t) = A(t) - D(t) \tag{1}$$

The delay for a vehicle arriving at time t is

$$w(t) = \frac{Q(t)}{c} = \frac{A(t) - D(t)}{c} = \frac{A(t)}{c} - t \tag{2}$$

The total delay to all travelers over the peak period is the area between $A(t)$ and $D(t)$, which equals

$$\int_0^{t_E} [(A(t) - D(t)]\mathrm{d}t \tag{3}$$

This idealized queue, combined with vehicle occupancies for HOVs and LOVs and the changes in freeway capacity for LOVs and HOVs, can be used to estimate the changes in person-delay and emissions from adding an HOV lane, adding an additional general purpose lane, or converting an existing lane to an HOV lane

2.2. Assumptions regarding delay

Recent research, some of it undertaken to inform revisions to the speed–flow relationships in the Highway Capacity Manual, has suggested that speed remains relatively constant until a freeway approaches capacity. at which point a queue forms and flow remains at capacity regardless of the queue length (Hurdle and Soloman. 1986, Hall and Hall, 1990, Banks, 1991, and Chin and May, 1991) The research supports a model in which (1) all delay is caused by queueing and none by increasing density *per se*, and (2) once the freeway reaches capacity, flow remains constant. In other words, the speed flow curve is a horizontal line at free flow speed until capacity is approached, at which point it begins to turn into a vertical line indicating constant capacity regardless of speed as shown in Fig 4.

2 3. Estimating the shift to HOVs

The probability of making a trip via HOV is a function of the attributes of (1) the HOV trip, (2) the trip via non-HOV (a single occupant vehicle in most cases), and (3) the person making the trip. HOV attributes include waiting time, travel time, time and inconvenience arranging the carpool, ambience in the waiting area and the HOV, and cost. Single occupant vehicle attributes include travel time, parking availability and cost, vehicle ambiance, driving conditions, and vehicle

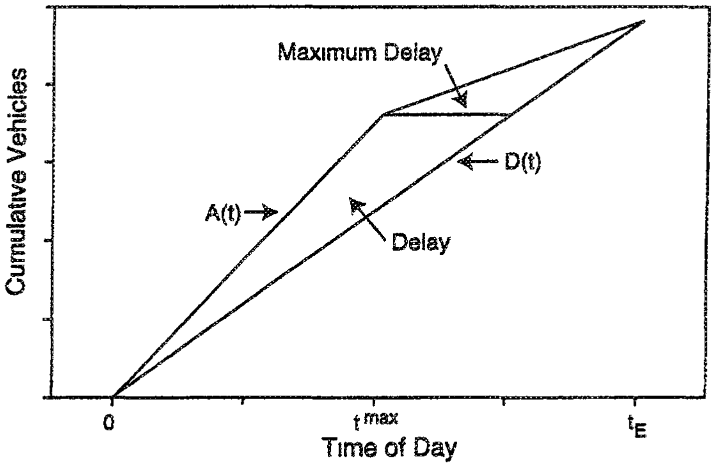

Fig 3 Idealized queue

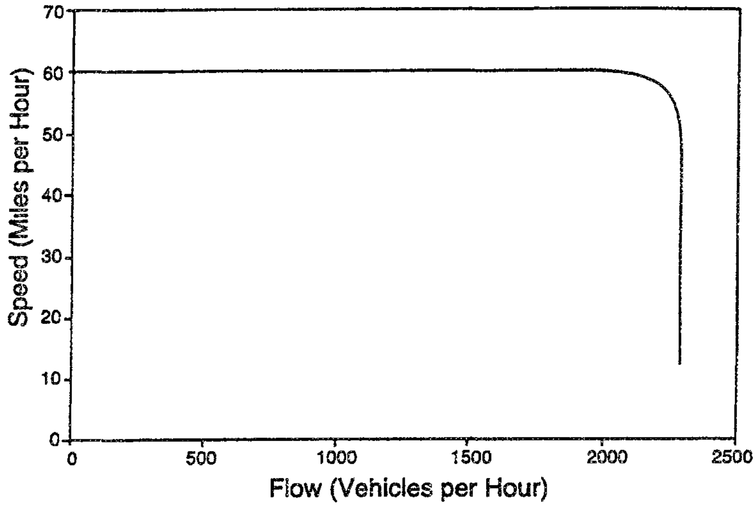

Fig 4 Freeway speed vs flow

operating cost. Traveler attributes include regularity and flexibility of working hours, work and home location, child care requirements, income, and availability of an automobile.

The probability that a particular individual will use an HOV can be represented by a logit model

$$p_{\mathrm{HOV}} = \frac{e^{\sum \beta_t H_t}}{e^{\sum \beta_t H_t} + e^{\sum \beta_t L_t}} = \frac{1}{1 + e^{\sum \beta_t L_t - \sum \beta_t H_t}} = \frac{1}{1 + \Gamma e^{\beta_t (L_t - H_t)}} \tag{4}$$

where β_t are the coefficients of the attributes and the H_t and the L_t are the traveler and modal attributes related to the HOV and LOV trip, respectively When an HOV or general purpose lane is added, the only attributes that change are the travel times for the two modes. Therefore, all other attributes and their coefficients can be represented by a constant, Γ. As a result, the exponent of e is reduced to $\beta_t(L_t - H_t)$, where β_t is the coefficient of the travel time and L_t and H_t are the travel times via general purpose lanes and the HOV lane respectively The same coefficient for travel time is assumed for both HOVs and LOVs.

Each individual has different personal and modal attributes, and consequently different probabilities of using each mode, represented by a different Γ Some people can not shift to an HOV. They may have irregular or unpredictable trip starting times, they may have an unusual trip origin or destination, they may need their vehicle at their destination, or they may need to transport equipment, materials, or children Each region has different travel patterns and opportunities for HOV travel The extent of the shift depends on these factors as well as the travel time advantage resulting from the HOV lane. Figure 5 shows three hypothetical distributions of the proportion of people using HOVs. The vertical axis shows the proportion using HOVs. The horizontal axis shows the *freeway* travel time differential between HOV and LOV (not the *total* travel time differential). Without an HOV lane, this differential is 0

The highest curve represents the distribution in an area in which most of the people who could possibly travel via HOV are already doing so. This might be an area with a strong urban center, high congestion in the center, and good bus service The middle curve might represent the distribution in an area where there are unutilized opportunities for ridesharing and transit. The lowest curve represents the distribution in an area where few people use HOVs, perhaps because transit service is poor or non-existent and opportunities for convenient carpooling are limited. In all three cases, some people are using HOVs when the travel time differential is zero. When the freeway travel time for HOVs is reduced, increasing the differential between LOV and HOV travel time, $L_t - H_t$, to V, the proportion of people using HOVs increases in all three cases. But the increases in the proportion of people using HOVs, S_1, S_2, and S_3, are quite different In deciding whether to build an HOV lane or not, the likely shape of this curve should be considered

The distributions in Fig. 5 were the sums of the probabilities of individuals using an HOV for each value of $L_t - H_t$. Despite differences in each person's probability of using an HOV, for

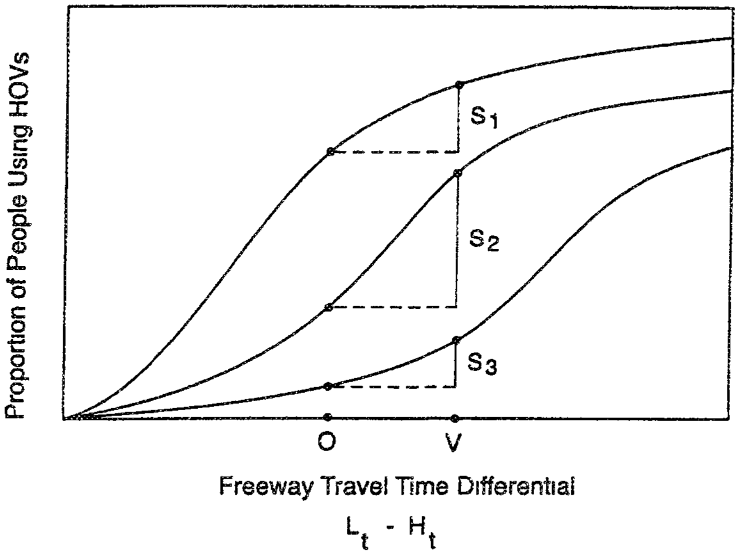

Fig 5 The proportion of people shifting to HOVs depends on the propensity to use HOVs

simplicity, the model used in this research assumes that all travelers have the same probability of using an HOV. This gives the upper limit to the number of people who might shift mode, as is shown in the Appendix

Given this assumption, the expected proportion of people using HOVs is equal to the individual probability of using an HOV

$$P_{\mathrm{HOV}} = \frac{1}{1 + \Gamma e^{\beta_t (L_t - H_t)}} \tag{5}$$

Because the travel time differential, $L_t - H_t$, is initially 0, Γ can be calculated from the proportion of people initially using HOVs Estimation of β_t is another matter Published HOV lane evaluations do not include data that link the proportion of people using HOVs to the changing travel time differential or to shifts from other times and routes, so it has not been possible to estimate travel time coefficients from experience with real HOV lanes Therefore, a range of values based on the mode choice literature was used −0 02 min^{-1} of round trip travel time (Small, 1977), −0.02, −0.03 −0 04, −0 06 (McFadden and Talvitie, 1977); −0 0082 (Koppelman, 1983); and −0 012 and −0.016 (Kollo, 1986) Using this wide range of values increases the likelihood that the true value is considered and allows an examination of the effects of this coefficient on results.

2.4. Interaction of the travel time differential and mode shift with an HOV lane

Travel times on the general purpose lane will change over the course of the peak period, as can be seen in Fig. 6 from Wade *et al* (1992), which shows travel times for the general purpose and HOV lanes on the Katy freeway in Houston during the peak period The proportion of people entering the freeway at a particular time who will use HOVs depends on the travel time differential, $L_t - H_t$, at that particular time, but the travel time differential, in turn, depends on the proportion of people who, up to that time, have used HOVs. This travel time differential is the difference between the delay for the HOVs and the delay for LOVs. To calculate these delays we modify eqn (2), letting $A(t)$ represent cumulative *person* arrivals at the freeway, $P(t)$ represent cumulative person arrivals in HOVs, L and H represent LOV and HOV average occupancies, and C_L and C_H represent capacities on the general purpose and HOV lanes, respectively The congested period begins at time $t = 0$; congestion on the HOV lane begins at time t_H Delay for the LOVs entering the freeway at time t is

$$w_L(t) = \max\left\{\frac{\frac{A(t)-P(t)}{L}}{C_L}, 0\right\} = \max\left\{\frac{A(t) - P(t)}{LC_L} - t, 0\right\} \tag{6}$$

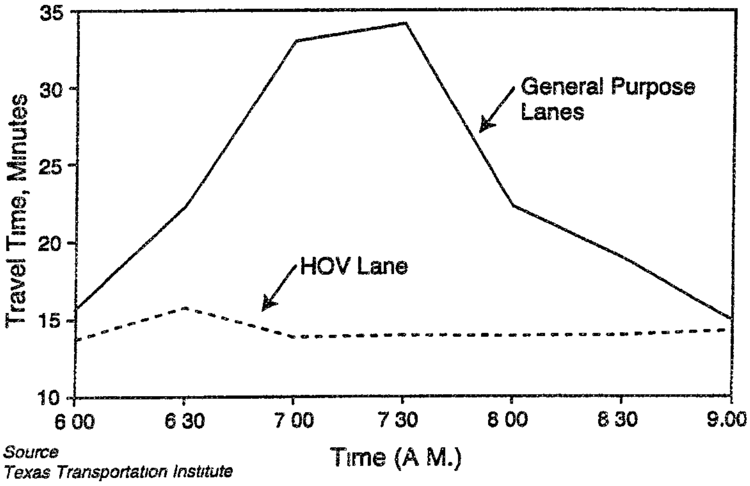

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Fig 6 Katy freeway mainlanes and HOV lane a.m travel time

and for the HOVs is

$$w_H(t) = \max\left\{\frac{P(t) - P(t_H)}{HC_H} - (t - t_H), 0\right\} \tag{7}$$

$P(t)$, the cumulative person arrivals in HOVs by time t, in turn depends on the travel time differential $L_t - H_t$ at time t, which equals $w_L(t) - w_H(t)$

$$P(t) = \int_0^t [a(x)P_{\mathrm{HOV}}(x)]\mathrm{d}x = \int_0^t a(x)\frac{1}{1 + \Gamma e^{\beta_t[w_L(x) - w_H(x)]}}\mathrm{d}x \tag{8}$$

where

$$a(x) = \frac{\mathrm{d}A(x)}{\mathrm{d}x} \tag{9}$$

Equation (8) is not solved analytically, but is the basis for calculating $P(t)$ numerically over hundredth of an hour intervals. Using this method, $P(t)$ equals the value of the expression inside the integral evaluated at t plus the sum of this expression for all previous values of t The travel time differential, $w_L(t) - w_H(t)$, is also calculated for each hundredth of an hour and used to calculate $P(t)$ for the subsequent hundredth hour interval. For people entering the freeway during each interval, total person-delay, vehicle-delay, and vehicle-trips are calculated These are summed to obtain total person-delay, vehicle-delay, and vehicle-trips for the entire peak period. Any standard spreadsheet software can be used for the calculations. These calculations are made for two cases involving HOV lanes. (1) an added HOV lane and (2) an existing lane converted to an HOV lane Similar calculations, without the HOV adjustment, are made for two cases without HOV lanes: (1) no change in the freeway and (2) an added general purpose lane. Total vehicle-delay and vehicle-trips are used to calculate emissions based on factors from the California Air Resources Board emissions model for 1993. Benefits are compared in terms of average person-delay and emissions.

2.5 Effects of model assumptions

The model contains a number of assumptions. They are summarized in Table 1 and treated at greater length in the sensitivity analysis in the Appendix The assumptions in the first group make an HOV lane appear to have greater individual benefits relative to a general purpose lane than would actually be the case. The assumptions in the second group would not change the ranking of the alternatives in terms of individual benefits. The effects of the assumptions in the third group would depend upon the situation. The effects of these last two assumptions are not as strong as the overall effects of the assumptions that lead to an overstatement of the benefits of an HOV lane

Table 1 Effects of assumptions

Assumptions that lead to an overstatement of the benefits of an HOV lane relative to a GP lane	
Identical probabilities of using an HOV	The mode shift with identical probabilities is always greater than with different probabilities
No downstream entries	Downstream entries cause measured delay to be more than actual average delay—more delay favors an HOV lane
No reduction in convenience due to shift to HOV	Only the time saving beyond that necessary to induce a shift is a benefit
All HOVs use the HOV lane	Benefits of HOV lane are less if fewer vehicles use it
People do not drive to meet the carpool or bus	Driving to meet the carpool or bus would increase emissions substantially
Assumptions that do not change the ranking of an added HOV lane versus an added GP lane	
No route shifts	Benefits are larger with larger route shifts, and larger delay reductions result in larger route shifts
No shifts in trip start time	Larger delay reductions allow larger shifts in trip start times
No induced trips	Benefits from new trips are greater and costs of these trips are less with larger reductions in delay Air quality benefits of reduced delay are likely to be greater than air quality costs of induced trips
No vehicles entering and exiting the queue before the bottleneck	Benefits to these vehicles are greater with larger reductions in delay
Assumptions whose effects depend on the situation	
Vehicles arrive at a constant rate until the time of maximum delay and at a lower constant rate thereafter	If the arrival rate is linearly increasing and the time of maximum delay is less than 2/3 through the peak period, the relative benefits of an HOV lane will be understated, otherwise they will be overstated
Only HOVs use the HOV lane	Allowing cheating increases utilization of the HOV lane but reduces the incentive to use an HOV

relative to a general purpose lane Therefore, it is assumed that on balance the model overstates the benefits of HOV lanes relative to those of general purpose lanes

3 FINDINGS

The goals of this research were both to understand the factors that determine the relative effectiveness of HOV lanes and general purpose lanes and to determine the circumstances in which HOV lanes would be more effective. The sensitivity of relative benefits to these various factors is presented first. Then the circumstances in which HOVs are more effective are described

3 1. Sensitivity of relative benefits to initial conditions and assumptions

This was examined using a typical sensitivity to travel time and initial conditions similar to conditions where HOV lanes have been implemented (Turnbull, 1992)*. The use of other initial conditions would change the delay shown in the following charts but would not change the basic features and sensitivities. It was assumed that all HOVs used the HOV lane and all LOVs used the general purpose lanes

3 1 1 Initial proportion of HOVs This was found to be the most critical factor in determining the effectiveness of an HOV lane relative to a general purpose lane. Figure 7 shows the initial proportion of HOVs on the horizontal axis and the average person-delay on the vertical axis. All other factors were held equal. The graph shows four cases.

1. *No change*—the base case with no additional lanes;
2. *Conversion*—an existing lane is converted to an HOV lane;
3. *HOV lane*—add an HOV lane; and
4. *GP lane*—add a general purpose lane.

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*HOV lanes require two occupants per vehicle, average HOV occupancy is 2 3 people, the congested period is 3 h long, the initial maximum delay is 20 min and occurs midway through the congested period, there are initially three lanes, each lane has a capacity of 2000 vehicles per hour, and the travel time coefficient is assumed to be −0 04

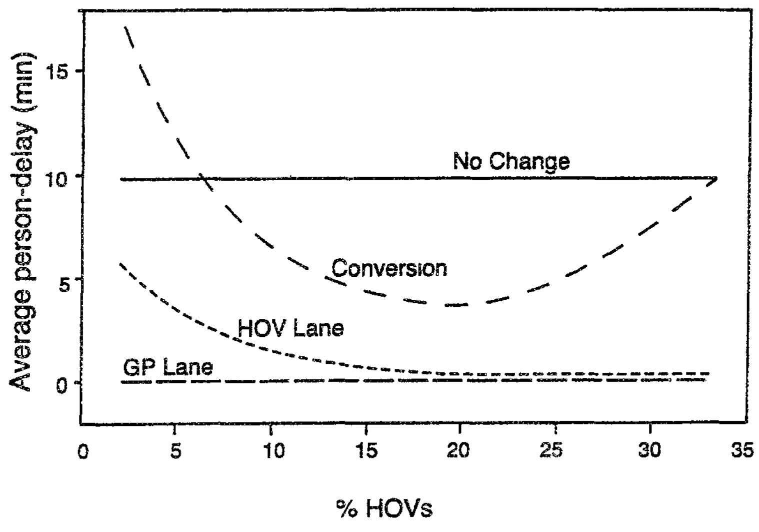

Fig 7 Effects of the initial proportion of HOVs

The curvature of the person-delay for the *conversion* and *HOV lane* cases results from two opposing effects The first effect is the diversion of existing HOVs from the general purpose lane, which reduces delay for HOVs and increases capacity available for LOVs, thus also reducing delay for LOVs The second effect is the shift from LOVs to HOVs, which reduces total person-delay by reducing LOV volumes In the *conversion* case, delay is reduced most if around 20% of vehicles initially are HOVs If fewer are initially HOVs, then there is less reduction due to the shift of existing HOVs to the HOV lane. If more are initially HOVs, the travel time differential is less and does not motivate as many people to shift to HOVs If 33% of the vehicles are initially HOVs, then the proportion of HOVs and the proportion of capacity devoted to HOVs will be equal (the freeway is assumed to have three lanes in each direction), resulting in no travel time advantage for HOVs and therefore no shift to HOVs and no benefit from HOVs shifting to the HOV lane If conditions were such that there were delay with an added general purpose lane, the *HOV lane* curve would have a similar U-shape But in this case delay is eliminated with an additional general purpose lane and, if the initial proportion of HOVs is 20% or greater, with an additional HOV lane, as well.

3 1 2 Initial maximum delay This is also a critical factor because it determines the delay differential, which is the motivation for the shift to HOVs (Fig 8). Although a higher initial maximum delay results in a higher average delay without a shift to HOVs, it also results in a higher travel time differential between the HOV and general purpose lanes, which induces a greater shift to HOVs This accounts for the lesser slope of the *HOV lane* line compared to the *GP lane* in Fig. 8.

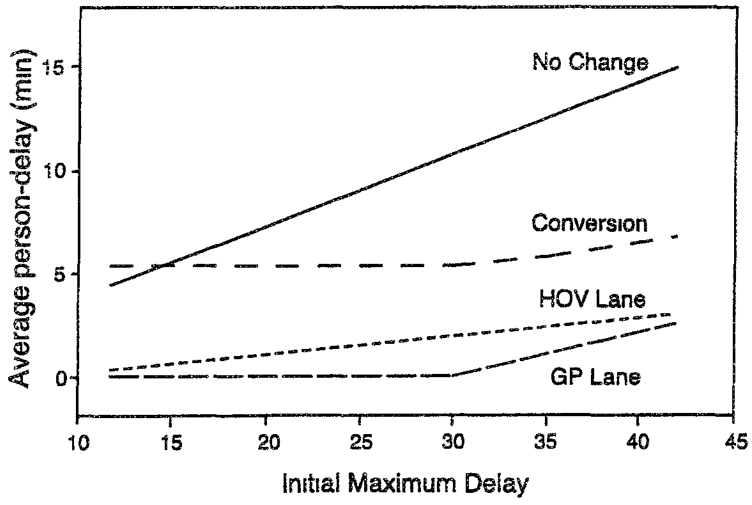

Fig 8 Effects of the initial maximum delay

These opposing effects are even more pronounced in the case of *conversion* line Figure 8 is based on the same initial conditions and assumptions as Fig 7 except that the initial proportion of HOVs is fixed at 0 09 and the initial maximum delay varies

Given these initial conditions, an added general purpose lane will eliminate delay if the initial rate of freeway arrivals is less than the capacity with the additional lane—in this case when initial maximum delay is less than 30 min

3.1.3 Travel time coefficient Figure 9 shows the effects of the travel time coefficient under the same conditions as in Figs 7 and 8. The stronger negative values of the coefficient appear on the left. Under the conditions assumed in this case, the travel time coefficient has relatively little effect with an added HOV lane because the travel time differential between the HOV lane and general purpose lanes is small If the initial maximum delay were greater or the initial proportion of HOVs smaller, the coefficient would have more effect. Its effect on delay with the converted HOV lane is much greater because of the greater travel time differential. With an initial proportion of HOVs of only 0 09, as in this example, a relatively high travel time coefficient is critical to the success of a lane conversion.

3.1 4. Effects of other initial conditions The HOV occupancy requirement, the proportion of buses, the length of the congested period, and the initial number of freeway lanes all affects HOV lane performance. Requiring three occupants per HOV, rather than two, lessens the relative effectiveness of HOV lanes because there is a much lower initial proportion of HOVs and it is harder to form carpools A higher average occupancy of HOVs, such as with a high initial proportion of buses, increases the relative effectiveness of HOV lanes because more people benefit from the HOV priority For a given initial maximum delay, a shorter congested period or the maximum delay occurring earlier in the congested period, means that the arrival rate of vehicles is higher and that therefore, adding capacity will be less effective in reducing delay Greater delay is more favorable to HOV lanes. Adding an HOV lane to a four lane freeway is relatively more effective than adding it to a three lane freeway because it is more highly utilized, since it represents a lower proportion of capacity

3.2 *Circumstances in which HOV lanes are more effective than GP lanes*

For a wide range of typical circumstances and assumptions, the average person-delay was calculated for the same four cases noted earlier no change, construction of an HOV lane, construction of a GP lane, and conversion of an existing GP lane to an HOV lane. The initial circumstances modeled were

(a) initial proportion of HOVs 0 05, 0 10, 0 15, and 0 20
(b) initial maximum delay 15, 25, and 35 min

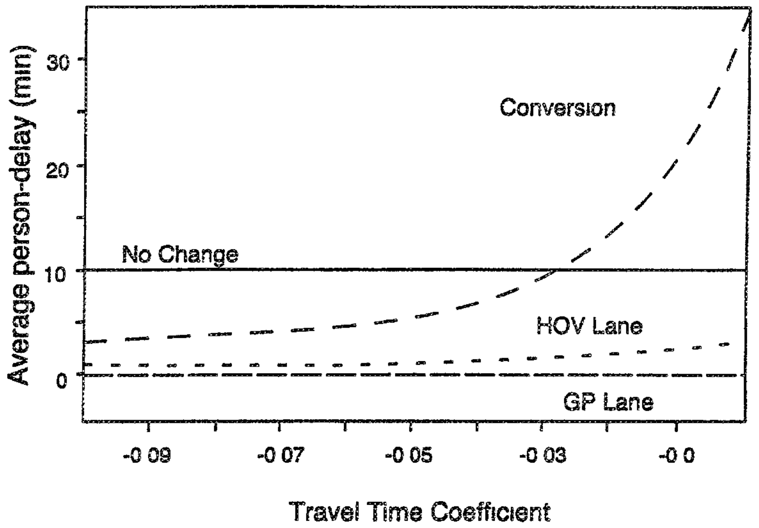

Fig 9 Effects of the travel time coefficient

(c) initial number of lanes· 3 and 4
(d) average HOV occupancy 2.15 (a typical occupancy without bus service) and 4 (a typical occupancy with relatively high bus use of the HOV lane)

These cover most of the circumstances in which HOV lanes are implemented (Turnbull. 1992) The travel time coefficients per minute of round-trip in-vehicle time were. 0.01, −0.02, −0.03, −0.04, and 0.05

In all cases, the occupancy requirement was assumed to be two. The model results for construction of an HOV lane or general purpose lane are shown in Fig 10 for an average HOV occupancy of 2.15, which is more typical of actual HOV lanes than the average occupancy of four The initial proportion of HOVs is shown on the horizontal axis and the average person-delay, on the vertical axis The upper HOVL line represents the case when the travel time coefficient is $-0.01\,\mathrm{min}^{-1}$ of round trip travel time, the lower line represents the case where the coefficient is −0.05. Figure 10(a–d) shows average person delay for construction of the two types of lanes when the maximum delay before the lane was added was 15, 25, 35, and 45 min, respectively. As noted earlier, the actual delay for freeways with both types of added lanes is somewhat understated because additional trips induced by the delay reduction will offset some of the delay reduction.

In these typical situations, construction of a GP lane eliminates or reduces delay to very low levels. Adding an HOV lane eliminates or reduces delay substantially when the initial proportion of HOVs is 0.15 or greater. The travel time coefficient is important when the initial proportion of HOVs is low but becomes less significant as the proportion approaches the proportion of capacity reserved for HOVs

Of these typical situations, only when the initial delay is great and when the initial proportion of HOVs is approaching, but has not reached, the HOV lane's proportion of freeway capacity does the highway perform better with an added HOV lane than with an added GP lane If the initial proportion of HOVs is 0.05%, an HOV lane is much less effective than a GP lane The relative performance of a highway with an HOV lane would be better with an average HOV occupancy of four, but it would still not be better than a highway with a GP lane unless the initial delay were more than 25 min and the initial proportion of HOVs was on the order of 15% or more

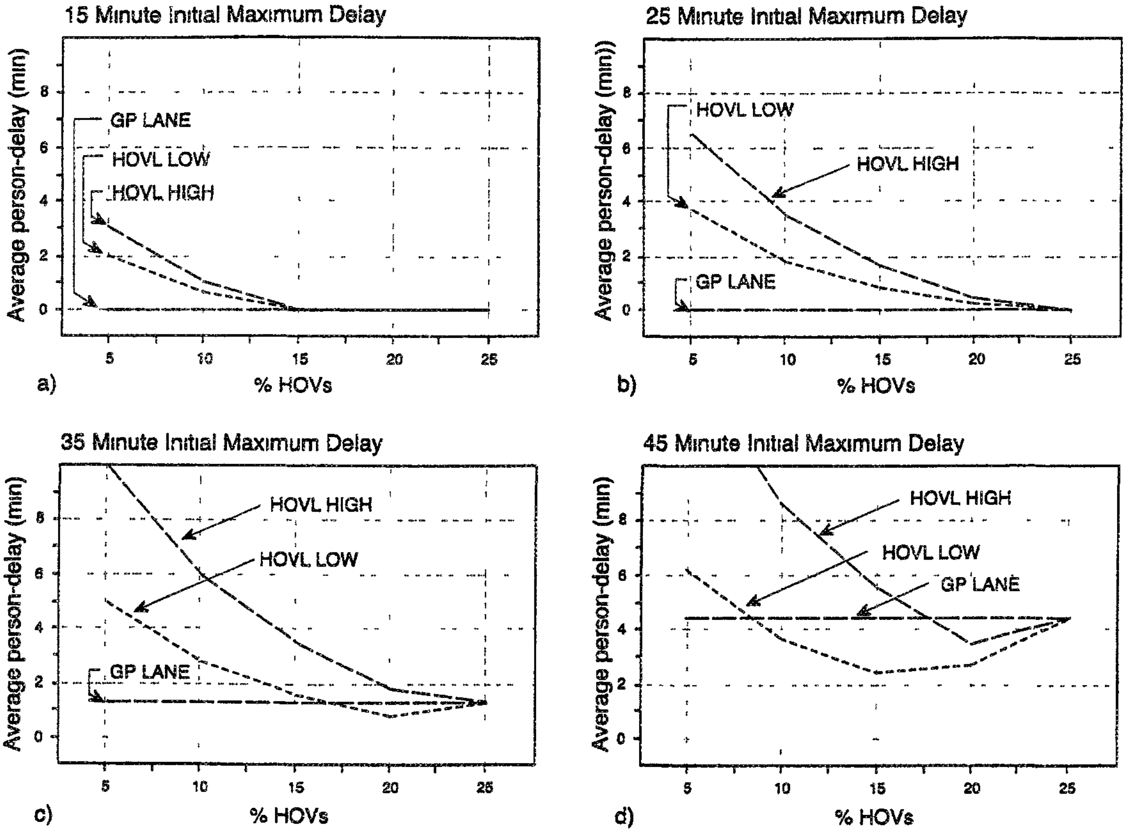

Fig 10 Effects of initial conditions on average delay

3.2 1 Effects on emissions. In general, because of the importance of delay-induced emissions of hydrocarbons and carbon monoxide, whichever lane has the lowest delay will also have the lowest emissions of these pollutants, and this will likely be a GP lane This runs counter to the conventional wisdom that adding an HOV lane reduces emissions more than adding a GP lane It is true that emissions of nitrogen oxides are reduced more with an HOV lane, but these are a small portion of the overall emissions reduction. Even the overall emissions reductions are small relative to the reductions that are projected to occur as a result of cleaner new vehicles replacing dirtier vehicles that are retired from the fleet

4 CONCLUSIONS

The primary effect of constructing an HOV lane is to reduce delay by increasing capacity The closer the initial proportion of HOVs is to the HOV lane proportion of freeway capacity, the more this effect dominates Unless substantial delay remains on the general purpose lane after the HOV lane is constructed, there will be little incentive for travelers to shift from a single occupant vehicle to an HOV. Even with a substantial freeway travel time benefit, the number of people who will be motivated to shift will be limited because of the inconveniences and longer off-freeway travel time associated with HOVs. HOV lanes are superior to GP lanes only if there is a substantial travel time differential between the HOV lane and the GP lanes and if the HOV lane is well utilized, which requires both a *high proportion of HOVs* and a *high volume of traffic.*

4.1 Current federal policy

Federal policies encourage construction of HOV lanes * These policies have led to a rapid expansion in the number of HOV lanes. Almost 1200 miles of new HOV lanes on freeways are currently proposed in addition to the nearly 700 miles in operation in mid-1994. (Fuhs, 1994). At the same time, federal policies discourage construction of GP lanes in areas that do not meet air quality standards Implicit in the preference for HOV lanes over GP lanes is the assumption that the reduction in emissions from the reduced trips and reduced congestion with an HOV lane will be greater than the reduction in emissions from reduced congestion with a GP lane This assumption is rarely challenged, perhaps because evaluations of HOV lanes typically do not compare their effects to those of general purpose lanes Furthermore, several factors can lead evaluators to incorrect conclusions First, if there is no delay on the HOV lane, all of the HOVs can pass through the bottleneck when they like, resulting in a higher number of HOVs during the peak hour even if there is no overall increase in HOVs. At the same time, if significant delay remains on the GP lanes, the volume of peak hour LOVs does not increase Consequently, if only peak hour data is considered, it will appear that the proportion of HOVs has increased when it has not actually increased over the entire congested period Second, differential shifts from other times and routes can make it appear that there has been a greater shift to HOVs than is actually the case. On one freeway in California where there were alternate routes, Highway 101 in Santa Clara County, the number of HOVs doubled during the peak two hours, but there was no change in the number of single occupant vehicles. Finally, construction of some HOV lanes has been accompanied by an increase in bus service, making the effect of the HOV lane difficult to isolate The level of analysis in HOV lane evaluations is often limited; many evaluations simply compare 'before' and 'after' peak hour vehicle occupancies, person volumes, and vehicle volumes per lane Few evaluations consider the dynamic nature of the differential in travel times between the HOV lane and the GP lanes

Federal policy is also influenced by concerns about growth. Construction of additional GP lanes is often opposed because it would induce additional trips. The growth inducing potential of HOV lanes is rarely acknowledged. People sometimes observe congestion on a newly improved road and assume that there has been little reduction in congestion. However, the measure of improvement is not the *absence* of congestion but the reduction in the *extent* of the congestion. Furthermore, shifts

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*The Intermodal Surface Transportation Efficiency Act does not allow federal funds to be used for projects that increase capacity for single occupant vehicles in areas that have not attained federal air quality standards unless the projects are part of an approved Congestion Management System Funds designated for Congestion Mitigation and Air Quality (CMAQ) may be used for HOV lanes but not for GP lanes of trips from other times and routes may give the impression of a much greater increase in trips than actually occurs. If people shift from alternate routes in response to reduced freeway delay, they benefit, as do the people remaining on the alternate routes People who can leave home later but still arrive at work on time also benefit, even if they experience some delay on the freeway Because it is congestion that suppresses trip making, any reduction in congestion, whether from an added GP lane, an added HOV lane, or even an improved transit system, poses the dilemma that it will induce additional vehicle travel. A GP lane will induce more vehicle-trips than an HOV lane or improved transit system only if it is more effective in reducing delay. Does this mean that adding capacity is futile? No It is clear that from a congestion standpoint, adding capacity will not make congestion worse than it otherwise would be—new trips will be induced only as long as the new delay is less than the old delay. Any *increased* congestion must come from real growth in demand resulting from population or activity growth. If the goal of transportation policy were to minimize vehicle travel, then *no* capacity should be added. The fact that this is not seriously considered may reflect the understanding that person-trips represent a benefit. Congestion could be considered a measure of the success of the system, rather than a measure of its failure. Our goal should not be to eliminate person-trips, but to reduce the costs that these trips impose One way to do this is to increase highway capacity, and constructing HOV lanes may not serve this goal as well as constructing GP lanes

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APPENDIX

A1 Effects of Assumptions

A1 1 Assumptions that lead to an overstatement of the benefits of an HOV lane relative to a GP lane

A1 1 1 Identical probabilities Assuming that all people have the same probability of using an HOV will give the upper bound to the expected change in the proportion of people using HOVs when an HOV lane is constructed To see this, consider the case with two groups of people, one with n_1 members with probability p_1 of using an HOV and the other with n_2 members with probability p_2 Assume that each group has the same coefficient, β_t, for the travel time differential, $v = L_t - H_t$, between HOV and LOV freeway travel times Given the mode choice equation

$$p = \frac{1}{1 + \Gamma e^{\beta_t v}} \tag{A 1}$$

then

$$\frac{\partial(p)}{\partial(v)} = -\frac{1}{(1 + \Gamma e^{\beta_t v})^2}\Gamma e^{\beta_t v}\beta_t = -\beta_t \times p(1-p) \tag{A 2}$$

and therefore

$$\Delta p = -\Delta v \beta_t \times p(1-p) \tag{A 3}$$

The actual expected change in the proportion using HOVs caused by a change in the travel time differential is the sum of the changes in the probabilities of using HOVs

$$E(\Delta P) = \sum E(\Delta p_i) = \frac{-\Delta v \beta_t}{n_1 + n_2}[n_1 p_1(1-p_1) + n_2 p_2(1-p_2)] \tag{A 4}$$

If the two groups were treated as one homogeneous population, p would appear to be

$$p = \frac{n_1 p_1 + n_2 p_2}{n_1 + n_2} \tag{A 5}$$

and the expected change in the proportion using HOVs would appear to be

$$E'(\Delta P) = E'(\Delta p) = -\Delta v \beta_t \left[\frac{n_1 p_1 + n_2 p_2}{n_1 + n_2}\right]\left[1 - \frac{n_1 p_1 + n_2 p_2}{n_1 + n_2}\right] \tag{A 6}$$

The difference between the apparent and actual expected change is

$$E'(\Delta P) - E(\Delta P) = \frac{-\Delta v \beta_t n_1 n_2}{(n1 + n_2)^2}(p_1 - p_2)^2 \tag{A 7}$$

Because Δv is always positive and β_t is always negative, the above is always positive, and treating the two groups as having the same probability of using an HOV, rather than having different probabilities, will always overstate the mode shift This result can be extended through induction The greater the differences in probabilities, the greater the overstatement

A1 1 2 No downstream entries Assuming no downstream entries leads to an overstatement of the delay, and greater delay favors HOV lanes relative to GP lanes, as was shown earlier Vehicles entering the freeway nearer the bottleneck will pass through the bottleneck before those entering upstream at the same time—in effect cutting in front of the upstream vehicles Consequently, if delay is measured from the end of the queue, it will be greater than the average delay in the queue, and measured delay will overestimate actual delay

A1 1 3. No inconvenience due to the shift to HOV The model assumes no inconvenience to people shifting from single occupant vehicles to HOVs In fact, they lose flexibility and probably increase overall travel time Thus, people who shift to HOVs do not obtain the full benefit of the freeway travel time saving, but only the saving beyond that needed to motivate them to shift modes Therefore, since the model calculates the full travel time saving, the relative benefits of HOV lanes are overstated

A1 1 4 All HOVs use the HOV lane The model assumes that all HOVs use the HOV lane This is not generally the case Some vehicles are not on the freeway long enough to enter and exit the HOV lanes. Furthermore, if the speed differential between the HOV lane and other lanes is large, it may take some time for vehicles to find an adequate gap in which to enter the HOV lane

A1 1 5. People do not drive to the bus or carpool If people drive to meet their carpools or to take the bus, the air quality benefit of the reduction in vehicle-trips due to the HOV lanes is greatly reduced because trip end emissions are substantial For example, trip end emissions of hydrocarbons, one of the precursors of ozone, are greater than emissions from driving five miles in uncongested traffic

A1 2 Assumptions that do not change the ranking of an HOV lane relative to a GP lane

A1 2 1 No route shifts If people are using alternate routes to the freeway to avoid freeway congestion, reducing delay on the freeway will induce some of them to return to the freeway As a result, freeway delay will be reduced less than estimated in the model However, overall delay on both the alternate routes and the freeway will be reduced *more* than estimated in the model because the people on the alternate routes are also benefiting from the increased freeway capacity Overall benefits will be greater for whichever type of lane initially reduces delay the most

A1 2 2 No shifts in departure time If capacity is increased at a freeway location where there is a queue, freeway users whose departure time is determined by the time they wish to arrive at their destination will alter their starting time because they can now leave later and still arrive on time As a result, the shape of the arrival curve at the freeway queue will change

The relationship between freeway delay and the choice of departure time is not straightforward Several people have studied it (Newell, 1988. Hendrickson and Kocur, 1981, Alfa, 1989, Mahmassani and Chang, 1987), but no way of estimating how it would change in response to a delay reduction in a particular situation has been devised

The upper and lower bounds for this shift when an HOV lane is added are shown in Fig A1 The upper bent line in Fig A1(a) shows the initial cumulative departures of both HOVs and LOVs from the trip origin, and the lower straight line shows the cumulative capacity of the freeway The total delay is the area between these two lines Fig A1(b) shows delay on the GP lanes after the addition of the HOV lane, but without any shift in departure times There is no delay for the HOVs

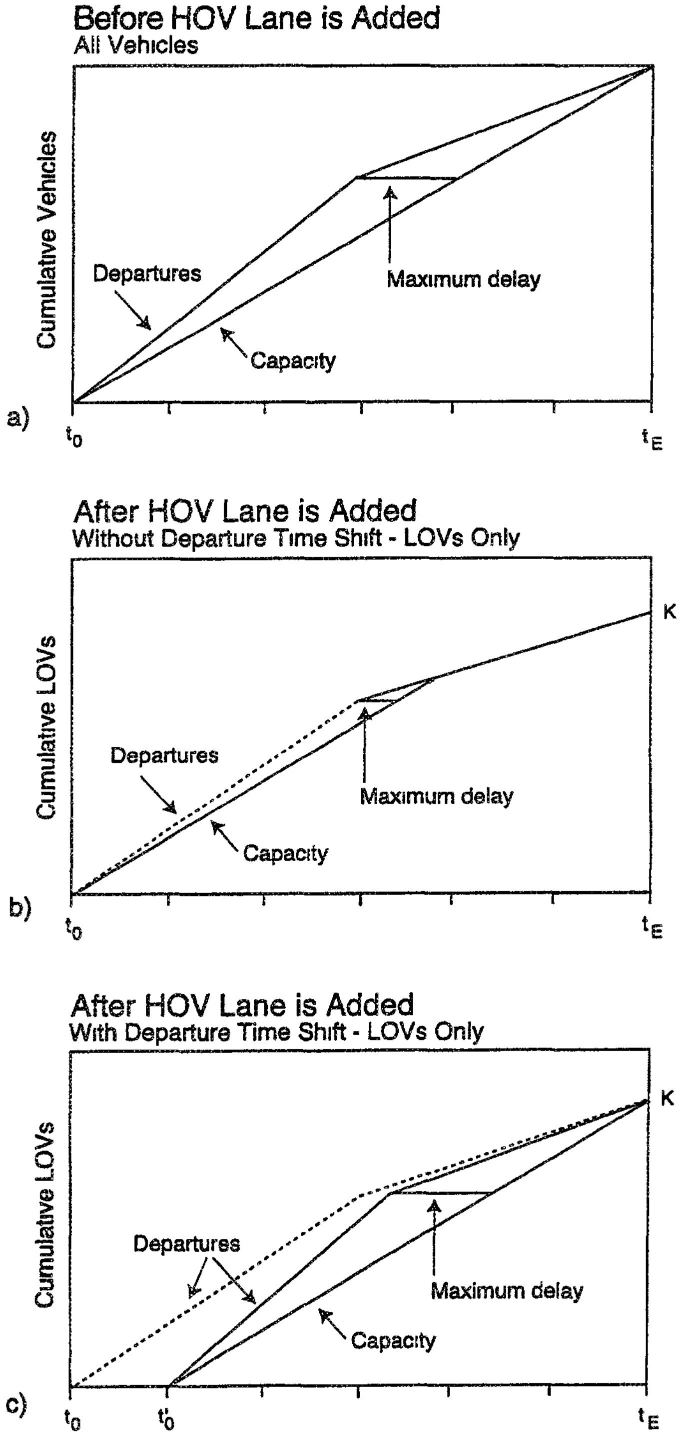

Fig A1 Limit on the departure time shift with an added HOV lane

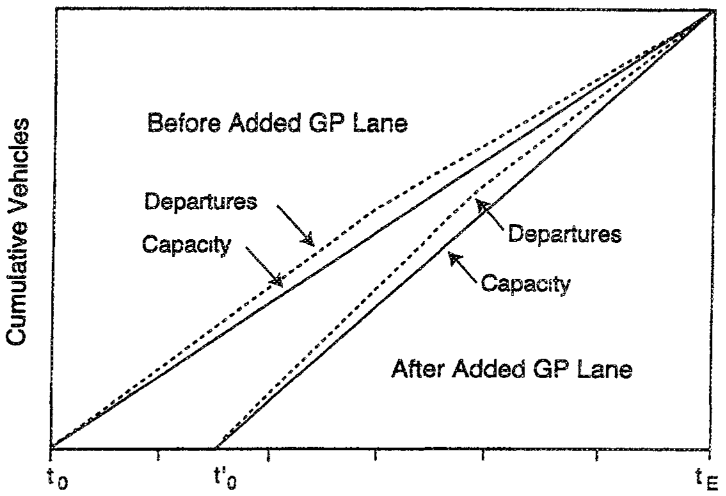

Fig A2 Limit on the departure time shift with an added GP lane

that have shifted to the HOV lane, only a fraction, *k*, of the original vehicles remain on the GP lanes This represents the lower bound on delay and is what the model calculates In this case, the delay is almost completely eliminated Figure A1(c) shows the upper bound on LOV delay, which would occur if everyone wished to arrive at the end of the congested period In this case there is no reduction in delay because the LOVs maintain the same maximum delay as before the HOVs were diverted to the HOV lane The additional time at the trip origin (sleeping in, perhaps) is equal to the space between the original (dashed) departure curve and the new (solid) departure curve in Fig A1(c) Figure A2 shows the departure time shift with the same conditions if a GP lane is added Instead of demand being reduced, as with an additional HOV lane, capacity is increased The lines on the left represent the initial cumulative departure and capacity curves, and those on the right represent the new curves The area between the two dashed departure curves represents the additional time at the trip origin Because delay is the same in both cases this is equivalent to the space between the two capacity curves With both the added HOV lane and the added GP lane the potential additional time spent at the origin (departure time shift) exceeds the potential delay reduction Because the potential departure time shift depends on the initial delay reduction, whichever alternative results in the greatest initial reduction in delay will also result in the greatest potential benefit from additional time at the trip origin

A1 2 3 Induced trips New trips are induced by the reduction in delay caused by building an additional lane Whichever type of lane reduces delay the most will encourage the most new trips This lane will have greater benefits because each new trip represents a benefit to the trip maker Furthermore, because of the lesser delay, these trips will impose a lower cost on the other travelers

A1 2 4 No vehicles entering and exiting the queue before the bottleneck These vehicles also benefit from any reduction in delay but this benefit is not included in the model Benefits to these vehicles are greater with greater reductions in delay

A1 3 Assumptions whose effects depend on the situation

A1 3 1 Vehicles arrive at a constant rate until the time of maximum delay and at a lower constant rate thereafter Data on delay suggest that this is an accurate model in many situations However, a linearly increasing and decreasing model may be more accurate in some situations In such a case, the maximum delay can occur no earlier than halfway through the peak period Total delay with the latter model will be greater than with the constant arrival model if the maximum delay occurs earlier than two thirds through the peak period, otherwise it will be greater with the constant arrival model Therefore, if the arrival pattern is linearly increasing and decreasing, and the maximum delay occurs between half-way and two thirds of the way through the peak period, this will tend to make the HOV lane look less beneficial relative to a GP lane than it actually would be

A1 3 2 Only HOVs use the HOV lane With a low level of enforcement, non-HOVs will use the HOV lane This increases the utilization of the lane and therefore tends to reduce delay However, it also undermines the incentive for people to shift to HOVs, and thereby eliminates one of the sources of delay reduction