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The University of California
Transportation Center

University of California
Berkeley, CA 94720

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Abstract

IN WHAT SITUATIONS DO HIGH OCCUPANCY VEHICLE LANES PERFORM BETTER THAN GENERAL PURPOSE LANES?

It is well known among HOV practitioners that the success of a high occupancy vehicle (HOV) lane in motivating people to shift to HOVs depends on maintaining a travel time differential between it and the adjacent general purpose lanes. This differential exists only if there is continuing delay on the general purpose lanes. The paradox inherent in this requirement--that HOV lanes as a congestion reduction measure require the *continuance* of congestion--is rarely noted. Because of this requirement for continuing congestion, it is not clear that construction of an HOV lane will always reduce delay or vehicle emissions more than construction of a general purpose lane. The objective of this research was to determine the circumstances in which this would be the case. The hypothesis was that such circumstances would be quite limited, and this proved to be the case.

A model was developed to calculate person-delay and emissions for four alternatives: add an HOV lane, add a general purpose lane, convert an existing lane to an HOV lane, and do nothing. The model required relatively few inputs: the beginning and ending time of the congested period, the time of the maximum delay, the length of the maximum delay, the number of lanes and the capacity per lane, the proportion of HOVs, and the average occupancy of HOVs and non-HOVs (hereafter referred to as LOVs for low occupant vehicles) Application of the model in typical situations showed that if the initial proportion of HOVs is .15 or greater, adding an HOV lane would eliminate or substantially reduce delay. 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 proportion of HOVs falls in a rather narrow range would an added HOV lane be more effective. In these cases the proportion of HOVs must be such that it allows good utilization of the HOV lane while maintaining a sufficient travel time differential to motivate a shift to HOVs.

Key words: High-occupancy vehicle lane, capacity, delay, planning, emissions

IN WHAT SITUATIONS DO HIGH OCCUPANCY VEHICLE LANES PERFORM BETTER THAN GENERAL PURPOSE LANES?

Current federal and state policies promote construction of high occupancy vehicle (HOV) lanes and discourage construction of general purpose lanes These policies reflect a widely held belief that because HOV lanes encourage ridesharing and transit use, they will be more effective in reducing congestion and emissions than additional general purpose lanes But it is well known by HOV lane practitioners that successful HOV lanes require the continuance of delay on the other lanes and that HOV lanes are not appropriate in every situation The purpose of this research was to determine those situations in which HOV lanes perform better than general purpose lanes

Constructing an HOV lane reduces person-delay by.

1) motivating people to shift to HOVs, thus reducing the number of vehicle trips,
2) giving priority to HOVs, letting them pass through the freeway bottleneck ahead of the other vehicles, and
3) increasing capacity

An HOV lane reduces emissions by reducing the number of vehicle trips and by reducing vehicle delay. Delay is reduced because trips are reduced and capacity is increased Constructing a general purpose lane *also* reduces person-delay and emissions by increasing capacity.

Although the person-delay, emissions, and fuel consumption benefits of HOV lanes derive from reductions in vehicle delay and vehicle trips, most current planning methods for HOV lanes use static transportation planning models which can not provide such measures, providing instead only peak hour travel times and volumes The translation of peak hour travel times and volumes into total peak period delay and trips requires many assumptions that are highly uncertain, such as the distribution of trips and effective capacity over time The model used in this research is dynamic and allows direct calculation of vehicle delay and vehicle trips It is easy to use and has limited data requirements, allowing resources for collecting and verifying data are concentrated on less data, thus tending to reduce data error.

The use of a model, rather than empirical research, was necessitated by the unintended effects of adding a lane--shifts from other routes, departure time shifts, and induced trips--and the lack of data available for measuring these effects Without appropriate data, these effects can be misinterpreted and erroneous conclusions drawn Shifts from other routes and times can be interpreted as induced trips Shifts of HOVs from other routes or times can be interpreted as increased HOV use. The model does not include these effects They can be dealt with by examining their effects on the model results Other effects that can be misinterpreted are the effects of increased bus service, which is sometimes coincident with the opening of an HOV lane and higher peak hour HOVs volumes resulting from the increased HOV capacity. The lack of this data also frustrated attempts to test the model in real world situations However, the author hopes to test the model with data on I-80 in the San Francisco Bay Area before and after the HOV lanes are implemented there

THE MODEL

The basic premise behind the model is that freeway delay is caused primarily by bottlenecks and that a congested freeway can be thought of as a moving line of vehicles waiting in a queue to pass through a bottleneck This assumption is consistent with recent research by Hall and Hall (1), Banks (2), and Chin and May (3) It is assumed that during the first part of the congested period, from time 0 to T_{max}, vehicles arrive at the queue at a steady rate that is greater than the capacity of the bottleneck (Figure 1) and that during the second part, from T_{max} to T_E, vehicles arrive at a rate that is less than capacity until the queue is dissipated Empirical data on travel times suggest that this is a reasonable approximation to actual arrival patterns The number of vehicles in the queue and the delay for a vehicle entering the queue are both greatest at T_{max} The area between the bent line A(t), representing the cumulative vehicle arrivals at the queue, and the straight line D(t), representing the cumulative number of vehicles passing through the bottleneck, represents the total vehicle delay All that is needed to describe A(t) and D(t) are the times when the delay begins and ends and is at its maximum, the maximum delay, and the capacity of the bottleneck, c, which is the slope of D(t).

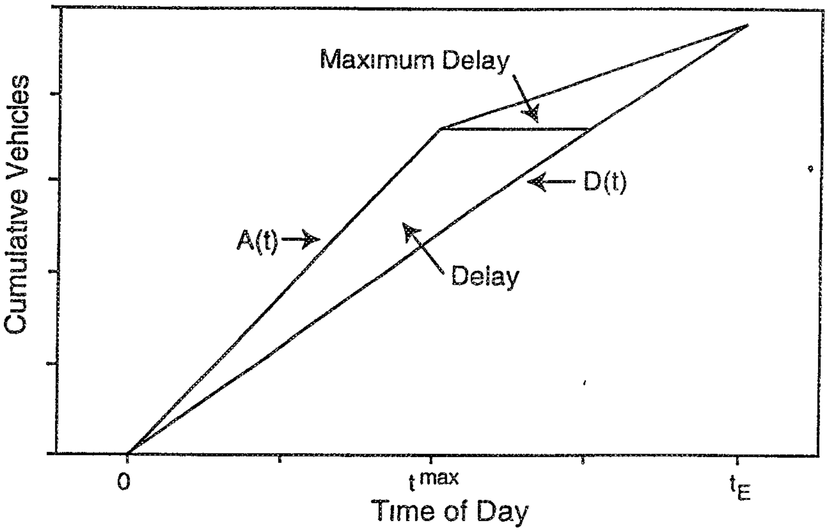
When an HOV lane is constructed, A(t) is reduced by the number of current HOVs that shift to the HOV lane and by the number of single occupant vehicles whose drivers shift to HOVs to take advantage of the reduced travel time on the HOV lane The former depends on the number of HOVs on the freeway before the HOV lane is constructed The latter depends on the travel time differential between the HOV lane and general purpose lanes after the HOV lane is constructed and the sensitivity of travelers' mode choices to travel time, which in turn depends on their opportunities for ridesharing and transit use and the extent to which these opportunities have been utilized, as well as their personal circumstances With the new demand, A'(t), on the general purpose lanes, total vehicle delay is reduced from the original area between A(t) and D(t) to the smaller area between A'(t) and D(t) The extent of the shift from single occupant vehicle to HOV, which is one of the determinants of A'(t), depends on the travel time differential, which in turn depends on A'(t)

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 low occupant vehicle (LOV), 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, comfort and perceived safety in the waiting area, comfort in the HOV, and cost Single occupant vehicle attributes include travel time, parking availability and cost, vehicle comfort, driving conditions, and vehicle operating cost Traveler attributes include such things as regularity and flexibility of working hours, work and home location, child care requirements, income, and availability of an automobile

Figure 1

Vehicle Arrivals and Departures At the Bottleneck



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

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

where the β_i are the coefficients of the attributes and the H_i and the L_i 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 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 $\beta_t(L_t-H_t)$, the product of the freeway travel time coefficient and the difference in freeway travel time on the general purpose lanes and HOV lane 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 cannot 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 The freeway travel time differential, $L_t-H_t = v$, between the HOV lane and general purpose lanes affects the mode choice of only those people who can use HOVs Therefore, the likelihood of a shift depends on other factors as well as the travel time advantage resulting from the HOV lane. However, despite the differences in people's probabilities of using an HOV, it is assumed, for simplicity, that all people have the same probability of using an HOV It can be shown mathematically that this is the upper limit on the number of people who will use HOVs Given the assumption of equal probabilities, the expected proportion of people using HOVs is equal to the individual probability of using an HOV

$$P_{HOV}=\frac{1}{1+\Gamma e^{\beta_t v}} \tag{2}$$

Because the travel time differential, v, is initially 0, Γ can be calculated from the proportion of people initially using HOVs Estimation of β_t is another matter HOV lane evaluations do not include data that link mode split with the changing travel time differential or with shifts from other times and routes, so it has not been possible to estimate travel time coefficients from experience with real HOV lanes No published estimates of travel time coefficients based on data that linked mode choice to the changing travel time differential caused by an HOV lane were found, and therefore, a range of values based on the mode choice literature was used Small's estimate of - 02 per minute of round trip travel time (4), McFadden and Talvitie's estimates of -0 02, -0 03 , - 04, - 06 (5), Koppelman's estimate of - 0082 (6), and Kollo's estimates of -.012 and - 016 (7). 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.

Interaction of the Travel Time Differential and Mode Shift

The proportion of people entering the freeway at a particular time who will use HOVs depends on the travel time differential 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

Under the assumption that all individuals making the trip have the same probability of using an HOV, the expected proportion of travelers entering the freeway at time t that will use HOVs is

$$P_{HOV}(t)=\frac{1}{1+\Gamma e^{\beta_t v(t)}} \tag{3}$$

where v(t) is the travel time differential between HOVs and LOVs entering the freeway at time t. The initial proportion of people in HOVs is

$$P_{HOV}(0)=\frac{1}{1+\Gamma} \tag{4}$$

because v(t)=0 at t=0

Delay for the LOVs entering the freeway at time t is

$$w_L(t)=\max\{\frac{\frac{A(t)-A_H(t)}{L}-tc_L}{c_L},0\}=\max\{\frac{A(t)-A_H(t)}{Lc_L}-t,0\} \tag{5}$$

and for the HOVs is

$$w_H(t)=\max\{\frac{A_H(t)-A_H(t_H)}{Hc_H}-(t-t_H),0\} \tag{6}$$

where:

A(t)=cumulative person arrivals on the freeway
A_H(t)=cumulative person arrivals in HOVs
L=average occupancy of LOVs
c_L=capacity for LOVs
H=average occupancy of HOVs
c_H=capacity for HOVs
t_H=the time HOV delay begins
0=the time LOV delay begins

$A_H(t)$ in turn depends on $v(t) = w_L(t)-w_H(t)$, which equals L_t - H_t referred to in the previous section.

$$A_H(t)=\int_0^t[a(x)P_{HOV}(x)]dx=\int_0^t a(x)\frac{1}{1+\Gamma e^{\beta_{tv}[w_L(x)-w_H(x)]}}dx \tag{7}$$

where

$$a(x)=\frac{dA(x)}{dx} \tag{8}$$

For each hundredth of an hour, the values of $A_H(t)$, v, and the delay for vehicles entering the freeway is calculated for four cases 1) no change in the freeway, 2) an added HOV lane, 3) an added general purpose lane, and 4) an existing lane converted to an HOV lane From the volumes and the delay at each point in time, total person-delay, total vehicle-delay, total person-trips, and total vehicle-trips can be calculated These measures form the basis for comparing the benefits of HOV lanes and general purpose lanes

Effects of Model Assumptions

The model makes a number of assumptions, which are summarized in Table 1 The first group of assumptions make an HOV lane appear to have greater individual benefits relative to a general purpose lane than would actually be the case The second group would not change the ranking of the alternatives in terms of individual benefits The effects of the third group of assumptions would depend upon the situation

Assumptions That Lead to an Overstatement of the Benefits of HOV Lanes Relative to a General Purpose Lane

Because, as noted above, the model assumes that everyone has the same opportunity and predisposition to use HOVs, and because this assumption overstates the proportion of people who will use HOV lanes, the model makes the HOV lane appear to reduce delay more than would actually be the case

The model assumes no inconvenience to people shifting from single occupant vehicles to HOVs In fact, they lose flexibility and probably overall travel time Thus, a person who shifts to an HOV does not obtain the full benefit of the saving in freeway travel time, but only the saving beyond that needed to motivate him or her to shift modes.

It 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

Table 1

EFFECTS OF MODEL ASSUMPTIONS

Assumptions That Lead to an Overstatement of the Benefits of an HOV Lane Relative to a General Purpose Lane	
Identical probabilities of using an HOV	The mode shift with identical probabilities is always greater than with different probabilities
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 General Purpose 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	
Only HOVs use the HOV lane	Allowing cheating increases utilization of the HOV lane but reduces the incentive to use an HOV

differential between the HOV lane and other lanes is large, it may take some time for vehicles to find a gap during which they can enter the HOV lane, and if the speed differential is small, HOVs are not motivated to move to the HOV lane

It is assumed that people do not drive to the bus stop or to the carpool meeting place However, they often do, and as a result, the vehicle trips are understated in the model Since a high proportion of total emissions occur when a cold engine is started and after a hot engine is stopped, this results in an substantial understatement of emissions

Assumptions That Do Not Change the Ranking of an HOV Lane Relative to a General Purpose Lane

The model assumes no route shifts If people who were using alternate routes in order to avoid freeway congestion return to the now less congested freeway, delay on the freeway 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 also benefit from the increased freeway capacity Overall benefits will be greater for whichever type of lane initially reduces delay the most The type of lane that appears superior will be even more superior than it appears

The model assumes no shifts in departure times. If capacity is increased at a freeway location where there is a queue, more 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. However, in doing so, they may experience more delay than if they had left at their original departure time because trips will tend to bunch up near the most common work starting times As a result, delay may be reduced less than estimated in the model, but there will be a greater benefit from the additional time travelers can spend at home or at work.

The model does not account for induced trips 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 and because the new trips will impose a lower cost on the other travelers.

Assumptions Whose Effects Depend on the Situation

The model assumes that only HOVs use the HOV lane With a low level of enforcement, LOVs 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

FINDINGS

Sensitivity to Initial Conditions and Assumptions

Initial Proportion of HOVs

The initial proportion of HOVs, that is the proportion of freeway vehicles that were HOVs before the HOV lane was constructed, was found to be the most critical factor in determining the effectiveness of an HOV lane relative to a general purpose lane Figure 2 shows the effects of the initial proportion of HOVs with typical initial conditions and behavioral responses

- o HOV lanes require 2 occupants per vehicle
- o the average HOV occupancy is 2 3 people
- o the congested period is 3 hours long
- o the initial maximum delay is 20 minutes and occurs midway through the congested period
- o there are 3 lanes
- o each lane has a capacity of 2000 vehicles per hour
- o the travel time coefficient is assumed to be - 04

The initial proportion of HOVs is shown on the horizontal axis and the average person-delay on the vertical axis All eligible HOVs and no LOVs are assumed to use the HOV lane

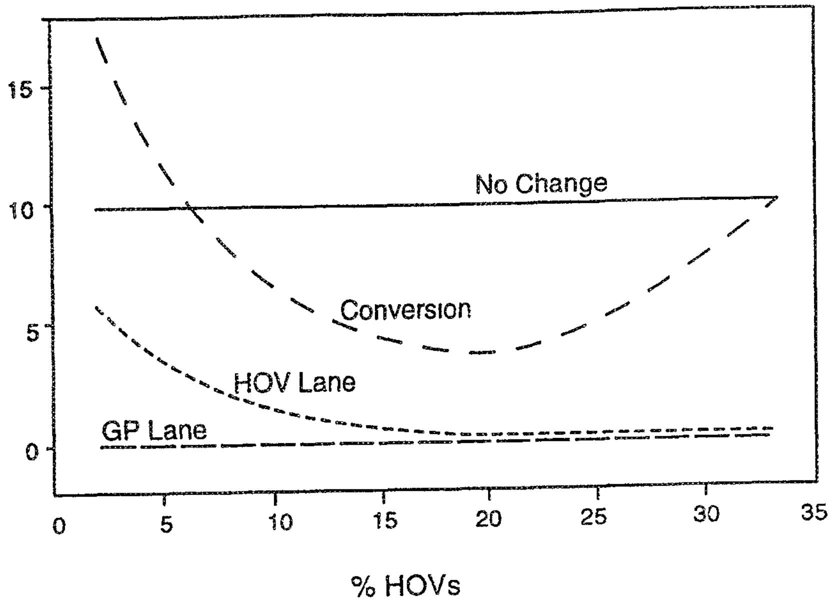
The curvature of the person-delay for the HOV lanes results from two opposing effects The first effect is the diversion of HOVs from the general purpose lane, which reduces HOV delay and increases capacity available for LOVs, thus also reducing delay for LOVs This effect is greatest for high initial proportions of HOVs The second effect is the shift from LOVs to HOVs, which reduces total person-delay by reducing LOV volumes The motivation for this shift is greatest when there is a low initial proportion of HOVs so that there is less delay reduction on the general purpose lanes However, low initial proportions of HOVs indicate a lower predisposition to use HOVs, which partially offsets the greater incentive to shift to an HOV. (This lower predisposition could be due to limited transit service or highly dispersed origins and destinations) Note that if the proportion of HOVs is equal to or greater than the proportion of capacity devoted to HOVs, the benefit of the HOV lane is lost and delay is the same as with a general purpose lane--an added general purpose lane in the case of an added HOV lane, or an existing general purpose lane in the case of a general purpose lane converted to an HOV lane Note also that with conditions such that there was delay with an added general purpose lane, the "Add HOV lane" curve would be U-shaped similar to the "Convert GP to HOVL" curve.

Initial Maximum Delay

This is also a critical factor because it determines the delay differential, which is the motivation for the shift to HOVs Although a higher initial maximum delay results in a higher average

Figure 2

Effect of the Initial Proportion of HOVs On Average Person-Delay



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 "Add HOV lane" line compared to the "Add general purpose lane" in Figure 3. These opposing effects are even more pronounced in the "Convert existing lane to HOVL" line. Figure 3 is based on the same initial conditions and assumptions as Figure 2 except that the initial proportion of HOVs is fixed at 09 and the initial maximum delay varies There will be no delay with an added general purpose lane 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 minutes.

Travel Time Coefficient

Figure 4 shows the effects of the travel time coefficient under the same conditions as in Figures 2 and 3. The stronger negative values of the coefficient appear on the left Under these conditions, 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

Effects of Other Initial Conditions

Requiring 3 occupants per HOV, rather than 2, lessens the relative effectiveness of HOV lanes because there is a much lower initial proportion of HOVs and it is harder to form carpools

Other things being equal, 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

Adding an HOV lane to a 4-lane freeway is relatively more effective than adding it to a 3-lane freeway because it is more highly utilized, since it represents a lower proportion of total capacity.

Comparison of the Performance of HOV Lanes versus General Purpose Lanes

For a wide range of typical circumstances and assumptions, the model was used to calculate the average person-delay with no change, construction of either an HOV lane or a general purpose lane, and conversion of a general purpose lane to an HOV lane The initial circumstances modelled were.

- initial proportion of HOVs 05, 10, 15, and 20
- initial maximum delay 15, 25, 35 and 45 minutes
- initial number of lanes 3 and 4
- average HOV occupancy· 2.15 (a typical occupancy without regular bus service) and 4 (a typical occupancy with good bus service)

Figure 3

Effects of the Initial Maximum Delay
On Average Person-Delay

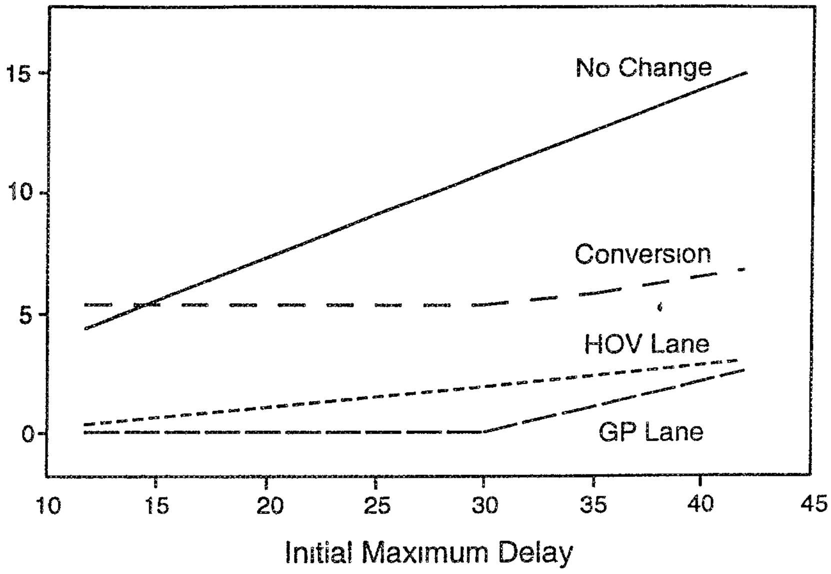
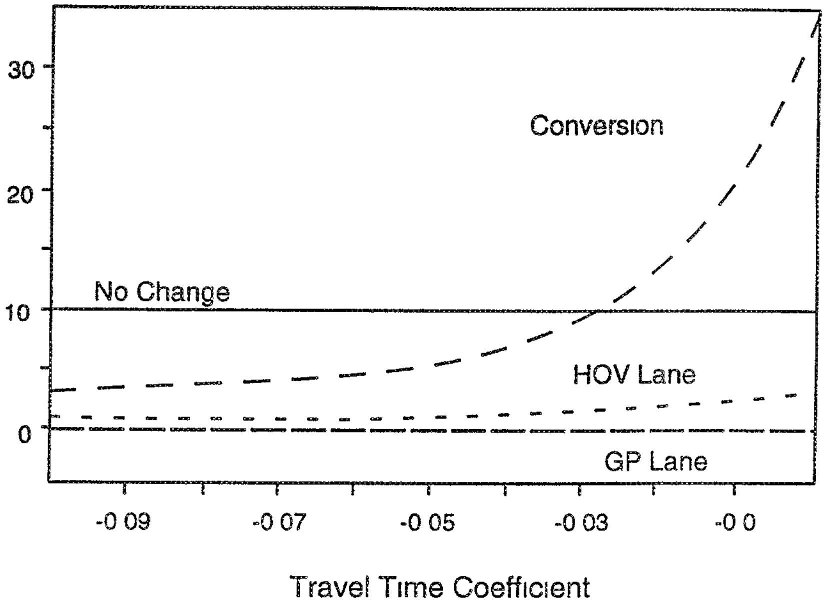


Figure 4

Effects of the Travel Time Coefficient On Average Person-Delay



These are typical of circumstances in actual HOV lane applications

The travel time coefficients covered the range of values found in the literature

- travel time coefficients per minute of round-trip in-vehicle time (indicating the sensitivity of mode choice to the travel time differential). -.01, - 02, - 03, - 04, and - 05

In all cases, the occupancy requirement was assumed to be 2 The model results are shown in Figures 5a, 5b, 5c, and 5d for the case when average bus occupancy is 2 15 The initial proportion of HOVs is shown on the horizontal axis and the average person-delay on the vertical axis. The straight horizontal line shows delay with an added general purpose lane; the two curved lines show the likely upper and lower limits for delay with an added HOV lane The upper line shows delay if the travel time coefficient is - 01 per minute of round trip travel time, the lower line shows delay if the coefficient is - 05 Figures 5a, 5b, 5c, and 5d show the delays for the two types of lanes when the maximum delay before the lane was added was 15, 25, 35 and 45 minutes, respectively As noted earlier, the actual delay for both types of lanes is somewhat understated because additional trips induced by the delay reduction will offset some of the delay reduction The delay for the HOV lanes will be understated more than that for the general purpose lanes because of the assumptions noted earlier

In these typical situations, construction of a general purpose 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 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

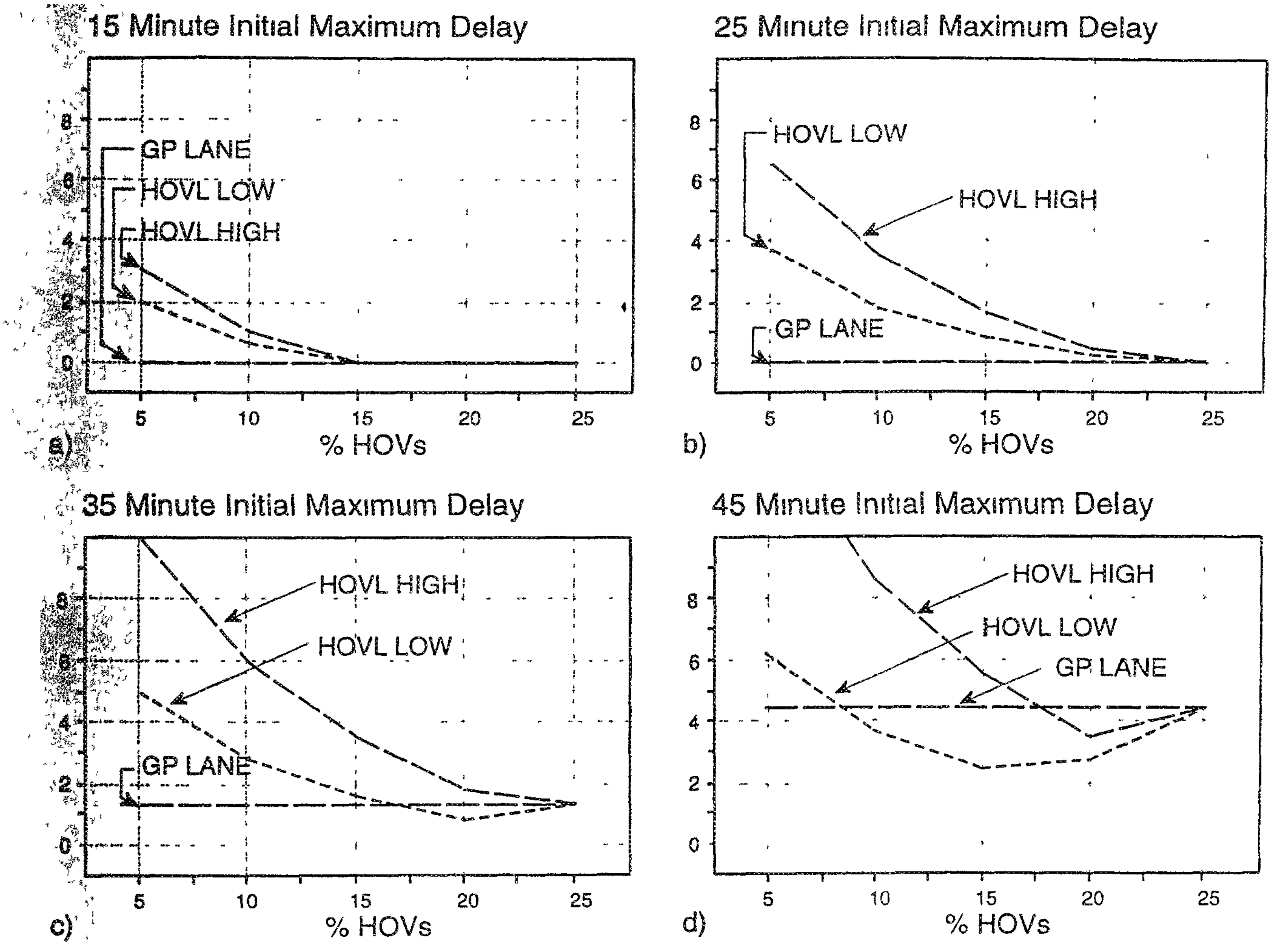
Of these typical situations, only those in which the initial delay is great and the initial proportion of HOVs is approaching but has not reached the HOV lane's proportion of freeway capacity does an HOV lane outperform a general purpose lane If the initial proportion of HOVs is 05%, an HOV lane is much less effective than a general purpose lane

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 have the lowest emissions of these pollutants, and this will likely be a general purpose lane This runs counter to the conventional wisdom that adding an HOV lane reduces emissions more than adding a general purpose 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.

Figure 5

Average Person-Delay with an Added HOV Lane Versus and Added General Purpose Lane



a) 15 Minute Initial Maximum Delay

b) 25 Minute Initial Maximum Delay

c) 35 Minute Initial Maximum Delay

d) 45 Minute Initial Maximum Delay

SUMMARY

The primary effect of constructing an HOV lane is to reduce delay by increasing capacity This effect is greater the closer the initial proportion of HOVs is to the HOV lane proportion of freeway capacity There will be little incentive for travelers to shift from a single occupant vehicle to an HOV, thus reducing vehicle trips and congestion, unless substantial delay remains on the general purpose lane after the HOV lane is constructed But even with a substantial freeway travel time benefit, the number of people who will be motivated to shift will be limited

HOV lanes are superior to general purpose lanes only if there is a substantial travel time differential between the HOV lane and the general purpose lanes *and* if the HOV lane is well utilized, which requires both a high proportion of HOVs and high initial delay indicating a high volume of traffic

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