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# Cost Effectiveness Of HOV Lanes

Final Report  
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**Washington State Department of Transportation**

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in cooperation with the

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# An Evaluation of the Cost Effectiveness of HOV Lanes

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## ABSTRACT

The cost effectiveness of high occupancy vehicle (HOV) lanes was analyzed by comparing the costs and benefits of existing HOV lanes with the hypothetical alternatives of doing nothing or adding a lane for general traffic. Three specific sites in the Seattle area were studied. A life cycle costing approach was used.

The main result of the study was that (for the three locations studied) the construction of HOV lanes was the most cost effective alternative. The "marginal net present value" of each of the projects was positive (on the order of \$50 to \$600 per commuter per year, depending on the specific comparison). The "marginal benefit/cost ratio" was greater than six for all cases.

Using extreme values for the elements of the model had little impact on the outcome of the study. Using extreme values for any factor, one at a time, did not come close to reversing any of the findings. Reversing the general finding of the study required extreme values for virtually

all of the factors. It is extremely unlikely that all the elements of the model were distorted in a direction to cause this outcome.

These findings showed that the three projects under consideration are very cost effective and should remain in place as HOV lanes. In fact, the investment of additional funds to improve the operation of these lanes could clearly be justified economically.

The methodology developed for this study was incorporated into an easy-to-use computer program that assesses the cost-effectiveness of the construction of HOV lanes in other locations. In order to save the costs of extensive data collection, the sensitivity analysis approach developed in this study proved to be a valuable tool in the analysis of sites for HOV lanes. Instead of collecting extensive data to precisely quantify the cost-effectiveness of potential HOV lanes, this method can be used to determine which factors can significantly affect the outcome.

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## PROJECT OVERVIEW

Freeway congestion is a significant and growing problem in the Seattle/King County area. A recent Federal Highway Administration (FHWA) research report indicated that the Central Puget Sound area has the sixth worst traffic in the country. Most of the suggested solutions to the problem entail significant political and financial difficulties. Some people say that the only way to solve the problem effectively is to construct additional freeways. However, government entities in this area, through the Puget Sound Council of Governments (PSCOG), have adopted a policy against the construction of new freeways. Some say that a light rail system would significantly relieve congestion. Others argue that the introduction of light rail would have a minimal effect on freeway congestion. However, funding for high capital alternatives such as rail or new freeways is not currently available.

A less costly alternative is to find ways to make the existing freeways more efficient in handling the demand. Several possible ways exist to accomplish this. One of these is the use of high occupancy vehicle (HOV) lanes, which is the subject of this report. Adding an HOV lane to a freeway potentially can increase the efficiency of a freeway in at least four ways: (1) by increasing the people-moving capacity of the facility) to provide room for growth in person-trips resulting from future development, (2) by offering high speed travel to a larger number of people (to decrease the average travel time), (3) by providing an incentive for people to share rides (to increase the number of persons carried per vehicle), and (4) by decreasing vehicle operating costs (by increasing the average speed and reducing the impact of stop-and-go traffic).

### Project Objectives

The objective of this study was to quantify the financial benefits that result from the introduction of HOV lanes and to compare those benefits with the costs incurred to implement them. The primary benefits of HOV lanes are travel time savings, reduced vehicle operating costs from smoother operation of the freeways, reduced costs through ridesharing and the ability to arrive at destinations without having to allow for delays. The primary costs are for the construction and maintenance of the facilities, the enforcement of the use of the lanes and the subsidy required to provide additional transit and other rideshare services.

### Approach

In order to compare these costs and benefits, three specific HOV lane facilities in the Puget Sound area were studied:

1. I-5 from Northgate to the King-Snohomish county line,
2. SR520 east of the Evergreen Point Bridge, and
3. I-405 south of I-90.

On each of these facilities, three alternatives were analyzed:

1. no additional lane construction ("do nothing"),
2. construction of an additional general purpose lane ("add general lane"), and
3. construction of an additional lane for transit and carpools ("add HOV lane").

For all three locations, the third alternative had actually already been implemented.

Many factors were involved in the calculation of the costs and benefits of the alternatives under consideration. To the extent possible, actual data were used in the calculations. However, for many factors, especially in future years, the values were unknown and assumptions were required. In order to test how critical these assumptions were, a sensitivity analysis was employed. A computer program, developed specifically for this project, was used to explore the impact of extreme assumptions on the final outcomes.

### Results and Implementation

The main result of the study was that (for the three locations studied) the construction of HOV lanes was the most cost effective alternative. The "marginal net present value" of each of the projects was positive (on the order of \$50 to \$600 per commuter per year, depending on the specific comparison). The "marginal benefit/cost ratio" was greater than six for all cases.

Using extreme assumptions for the elements of the model had little impact on the outcome of the study. Using extreme values for any factor, one at a time, did not come close to reversing any of the findings. Reversing the general finding of the study required extreme values for virtually all of the factors. It is extremely unlikely that all the elements of the model were distorted in a direction to cause this outcome.

These findings showed that the three projects under consideration are very cost effective and should remain in place as HOV lanes. In fact, the investment of additional funds to improve the operation of these lanes could clearly be justified economically.

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The methodology developed for this study was incorporated into an easy-to-use computer program that assess the cost-effectiveness of the construction of HOV lanes in other locations. In order to save the costs of extensive data collection, the sensitivity analysis approach developed in this study proved to be a valuable tool in the analysis of sites for HOV lanes. Instead of collecting extensive data to precisely quantify the cost-effectiveness of potential HOV lanes, this method can be used to determine which factors can significantly affect the outcome.

## Report Organization

The remainder of this report is divided into three sections. The first section contains the results of the study. The second describes the methodology used to forecast travel choices and to compute the costs and benefits. The third discusses the data collection and assumptions used to develop the factors for the cost model.

Details of the study are available in a separate technical report (1). That report contains (1) a complete review of the literature on cost analysis of HOV lanes and forecasting HOV lanes usage, (2) a description of the original study design and methodology proposed for this research, (3) details of computations used in the cost model, (4) details of the sensitivity analysis and (5) a documentation and description of the use of two computer programs related to this study. The first program is helpful in forecasting the use of HOV lanes under a large variety of conditions. The second program is the cost model that can be used to study other potential HOV lanes implementations. The report is available upon request by contacting the Washington State Department of Transportation:

Library  
Washington State Department of Transportation  
Transportation Building, KF-01  
Olympia, Washington 98104

The report is also available on a cost-reimbursable basis from the Washington State Transportation Center:

Washington State Transportation Center (TRAC)  
135 More Hall, FX-10  
University of Washington  
Seattle, Washington 98195

## PROJECT RESULTS

One of the objectives of this study was to determine the cost effectiveness of three HOV lanes in this region: I-5 north of Northgate, SR520 east of the Evergreen Point Bridge and I-405 south of I-90. Those results are summa-

ri- zed here. A second objective of the study was to determine how sensitive the cost effectiveness results were to the values for the elements of the cost models. The second part of this section deals with this question.

## Cost Effectiveness

Two measures were used to analyze the relative cost effectiveness of the third alternative compared with either the first or second ones. The first measure was the "marginal net present value." This measure is the difference between the "net present value" of the third alternative and those for the other two. The "net present value" is calculated by subtracting the present value of all the costs of an alternative from the present value of all the benefits. If the "net present value" of the third alternative were found to be larger than that of either of the other two (in other words, if the "marginal net present value" were positive), the HOV lanes would be cost efficient to construct.

The second measure was the "marginal benefit/cost ratio." This measure is calculated by dividing the difference in the benefits of two alternatives by the difference in their costs. For instance, if \$20 million more benefits can be realized from the construction of HOV lanes than from doing nothing and the extra costs are only \$5 million, then the "marginal cost/benefit ratio" is four. If this measure is greater than one, then for every dollar spent, the return is greater than a dollar.

Table 1 shows the cost effectiveness indicators for the three locations. Since the "marginal net present value" was positive for all comparisons, the numbers can be thought of as total savings resulting from implementing HOV lanes rather than following the other two alternatives. The total savings per commuter in comparison with doing nothing was between \$140 and \$600 per year. In comparison with adding a lane for general traffic, the savings worked out to between \$50 and \$80 per year. In all comparisons, the "marginal benefit/cost ratio" was greater than six. This means that each extra dollar spent to implement HOV lanes returned at least six dollars compared with the other two alternatives.

Table 2 shows the average overall trip time in the year 2000 for each alternative. HOV lane speeds are always faster than in the general traffic lane. In addition, in the I-5 and SR520 cases, peak hour speeds in the general traffic lane were higher for the HOV alternative than either of the other two alternatives. The cost model showed higher speeds on I-405 in the general traffic lane when the added lane was open to all traffic than when it was used for HOV traffic. The following paragraphs discuss a caveat to this result.

Table 1. Cost Effectiveness Indicators

	Location		
	I-5	SR520	I-405
Marginal Net Present Value (million \$'s) – "add an HOV lane" compared with:			
"do nothing"	+146.5	+78.7	+180.1
"add a general lane"	+56.4	+31.0	+14.8
Marginal Benefit/Cost Ratio comparing "add an HOV lane" with:			
"do nothing"	9.08	11.99	15.12
"add a general lane"	7.05	7.83	6.69

Table 2. Average Trip Time in Minutes (All Modes) in the Year 2000

Alternative	Location		
	I-5	SR520	I-405
do nothing	27.10	32.84	32.81
add a general lane	23.66	25.25	19.76
add an HOV lane	23.51	23.53	22.42

I-5 north of Northgate. This corridor was a highly used and congested corridor. By the year 2000 there will be significant congestion under all alternatives. The "add an HOV lane" alternative came out so positively primarily because it led to a significant shift to HOV usage and offered much faster travel times to people using HOV lanes than either of the other alternatives did. According to the model, 25 percent more people will be in HOVs on I-5 because of the HOV lane in 2000 than would otherwise be the case. In addition, they would be going at least 20 mph faster than all traffic would be if there were no HOV

lanes. For a relatively small investment, significant savings in time and other personal costs resulted.

SR 520 east of the Evergreen Point Bridge. This project did not accommodate the volumes of HOVs that the other alternatives did, nor did the HOVs travel as fast. However, for a very low cost, capacity was added over the "do nothing" alternative and all traffic traveled at higher speeds. If the HOV lane had been made available to all traffic, the small additional capacity may have come close to matching the HOV lane's ability to improve speeds, but

it would not have led to a shift in mode from single occupant vehicles (SOVs) to higher occupancy vehicles. The overall savings from the HOV lane was substantial, especially considering the modest investment required.

I-405 south of I-90. The HOV lanes on I-405 clearly were more cost effective than the "do nothing" alternative. However, the net savings over the "add a general lane" alternative were muted to some extent by the apparent ability of the "add a general lane" alternative to move people faster than the "add an HOV lane" alternative. If the HOV lane on I-405 were available to general traffic, the capacity of the facility would be 50 percent greater than the "do nothing" alternative. According to this analysis, if a general lane had been added that section of highway would be running fairly smoothly in the year 2000. The caveat in this result, however, is that the demand used for the year 2000 was based on a lower capacity facility. A higher demand probably would not allow the highway to operate as fast as this analysis showed.

Even if general traffic could operate as fast as the analysis showed, people would have little incentive to shift to higher occupancy vehicles. That result was reflected in

the overall net savings shown for the "add an HOV lane" alternative over the "add a general lane" alternative. The personal savings from ride sharing would outweigh the (questionable) advantage that the general traffic lane would have over the HOV lane in travel speeds.

### Sensitivity Analysis

A sensitivity analysis was performed on all the factors used in the cost model for the I-5 corridor HOV lane. The complete results for all 50 factors may be found in the technical report. Using extreme values for any of the factors did not come close to reversing the basic outcome of the study. The ten most sensitive elements of the model were determined for each of the alternative comparisons and are shown in Figures 1 and 2. These figures show the resulting cost effectiveness measures in the worst case for each factor. They are listed in order of sensitivity. One can see that, by the tenth most sensitive factor, the worst case assumption has little impact on the cost effectiveness outcomes. For three of these factors (percent preferring peak, discount rate, and value of time) rather extreme values were tested. Even with those, the lowest marginal benefit to cost ratio was greater than five.

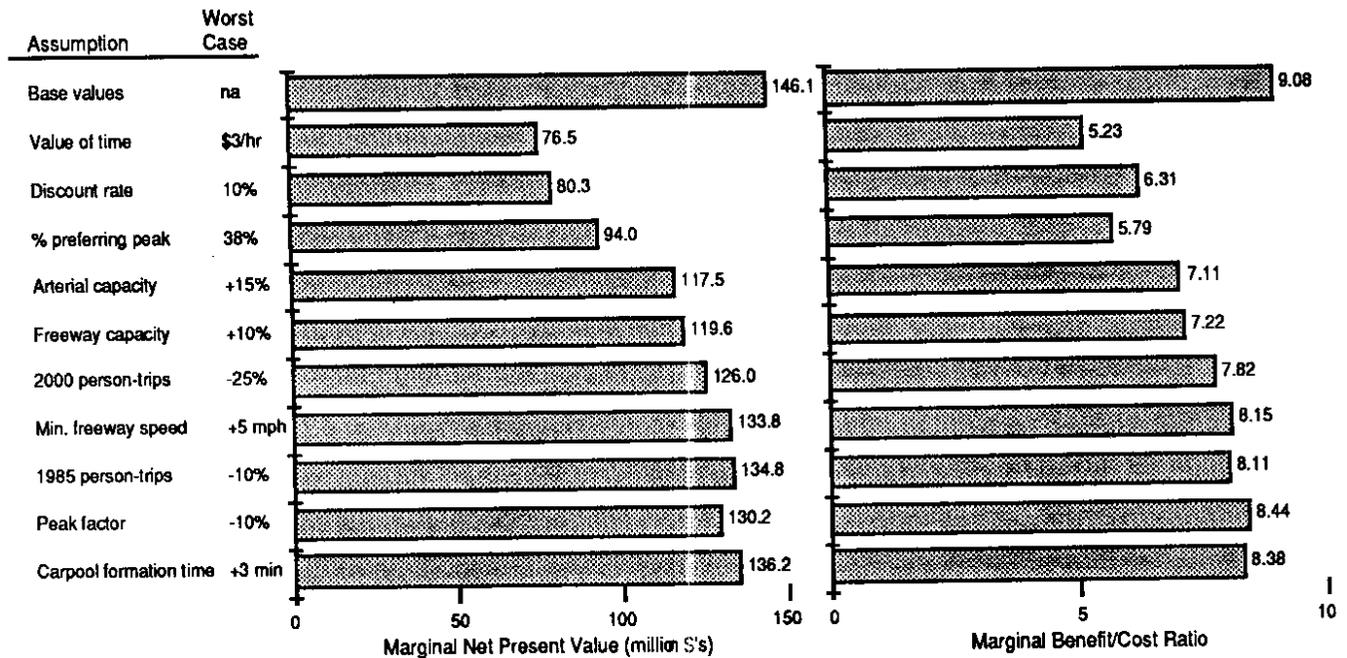


Figure 1. Worst Cases Compared with "Do Nothing" Alternative

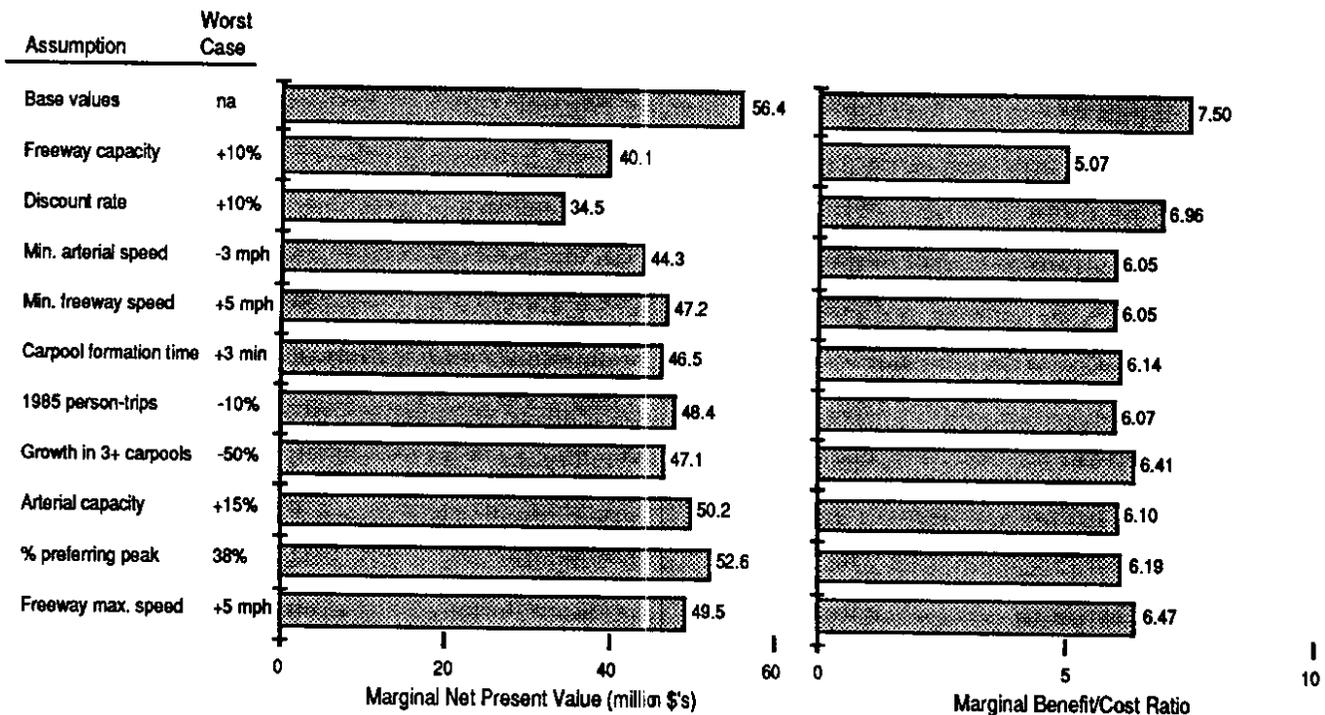


Figure 2. Worst Cases Compared with "Add General Lane" Alternative

All of the other factors related to how congested the corridor is or will become. The less congestion that occurs, the less favorable the HOV lanes are to both of the other alternatives. For instance, if freeway capacity had been underestimated, it would take longer to realize the benefits of the HOV lanes than the analysis showed. If there were more capacity on parallel arterials than had been assumed, it would also take longer before the HOV lanes could help improve the situation. The important point is that, if demand is assumed to eventually increase, errors in these factors only means that there would be a delay in the time it would take for the HOV lanes to become as cost effective as the analysis has shown.

A test was also conducted using combinations of extreme values. Worst case values for the elements of the model were added consecutively. For the comparison with the "do nothing" alternative, 26 values had to be changed before the HOV lane alternative was less cost effective. The comparison with the "add a general lane" alternative required 38 worst case values to cause a reversal. The likelihood of this many of the base values being off in the worst case direction is extremely low.

### COST EFFECTIVENESS EVALUATION METHODOLOGY

In order to evaluate the cost effectiveness of HOV lanes, the model was designed to address several issues in the measurement of costs and benefits for each alternative:

- How many people would shift from SOVs to car-pool, vanpools or transit if HOV lanes were built?
- To what extent do people depart early in order to arrive on time at their destination?
- Under what conditions do people shift from the freeway to a parallel arterial?
- What is the impact of congestion on speed and total travel time?

The cost model had to be relatively simple, since one of the aims of the research was to test the impact of a large number of assumptions in various combinations. On the other hand, it also had to deal with each of these issues in a realistic way in order to provide a valid comparison of the alternatives.

In order to accomplish these multiple goals, some simplification was necessary. Instead of trying to analyze the travel patterns of people between multiple zones of origin and destination, average trip lengths were employed. Distinctions were drawn among the modes under consideration, but the model represented the average person's trip within that mode.

Corridor travel was represented as consisting of only two possible paths, the freeway and parallel arterials. In places such as the I-5 North corridor, multiple arterial paths are available, but in this model they were all represented as one. As shown in Figure 3, trip length on the freeway segment and the parallel arterials were considered equal, as was the access to each of them.

Average trip speeds and times were employed in the analysis. Congestion can vary a great deal from day to day, depending on weather, construction and accidents. Even though the variability in congestion by itself is an important issue in travel choices, it was beyond the scope of this study to deal with it explicitly.

### Overview of the Model

Figure 4 is a flow diagram showing how the cost model works. The model computes all of these factors for six different scenarios. For each of the three alternatives, ("do nothing," "add a general lane" and "add an HOV lane"), costs are computed for 1985 and the year 2000 resulting in six (3 x 2) scenarios. These years were chosen primarily because person-trip forecasts and other factors for those years were available from the PSCOG's modeling efforts. In order to calculate costs for 20 years, a straight line is assumed to pass through these two points.

### Modal Assignment

First, the peak period person-trips for each alternative are assigned to different modes. Values for the number of carpools, vanpools and transit trips are discussed in the next section. The model assigns person-trips to single occupant vehicles (SOVs) by subtracting the number of people in the higher occupancy modes from the total number of person trips occurring during the peak period.

### Path Assignment

Second, a proportion of the trips are assigned to the parallel arterials based on the relative capacity of the arterials. This proportion is adjusted on an iterative basis to minimize the total travel time for all the people travelling through the corridor. The optimum total travel time is a legitimate criterion for optimization since it reflects the fact that each traveler is able, on a day-to-day basis, to

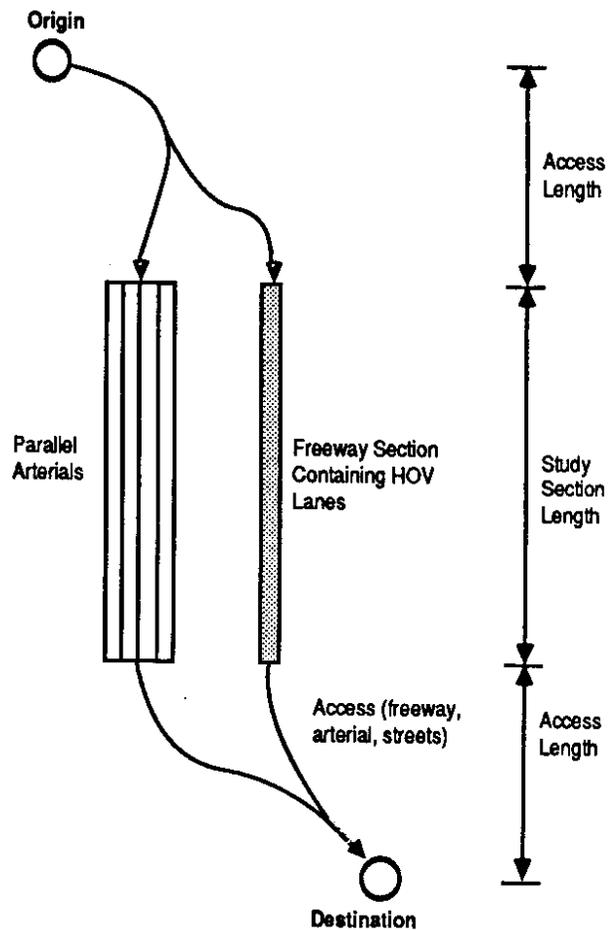


Figure 3. Schematic Representation of Trips Using the Cost Model

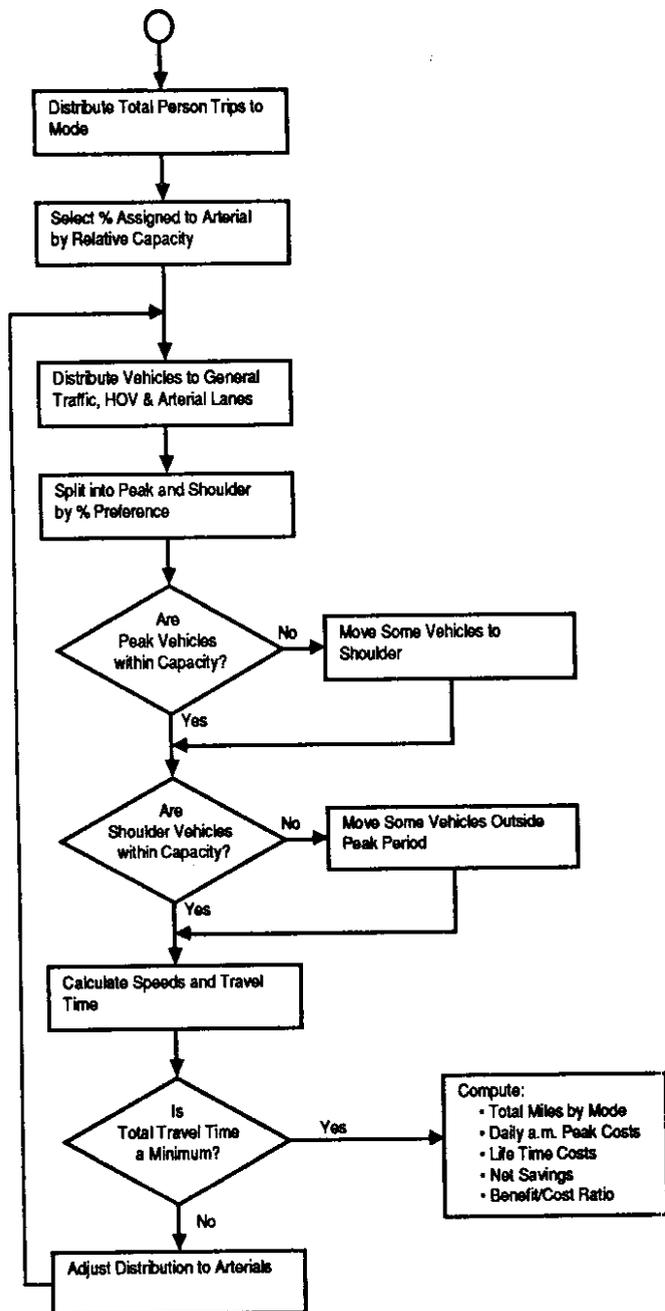


Figure 4. Flow Diagram for Cost Model

choose between the mainline and the arterial, depending upon which one makes the trip faster.

The third step is to assign the HOVs to HOV lanes if lanes are part of the alternative. The model assumes that all HOV vehicles travel on the HOV lanes if they are available and if they provide faster travel speeds than the other alternatives. If there are no HOV lanes, HOVs are assumed to be distributed the same as all other vehicles.

After the HOVs have been assigned, the model splits the remaining traffic between the freeway and parallel arterials according to the percentage determined during the iterative optimization process.

### Temporal Assignment

The next step is to split the peak period traffic between the peak hour and the shoulder of the peak. The model assumes that the peak period is three hours, with a two hour shoulder split on either side of the peak hour. One important element of the model is the percentage of people preferring to travel in the peak hour. This percentage is influenced by the extent and availability of flexible working hours.

### Capacity Checks

The model then checks to determine if the people preferring to travel during the peak hour can be accommodated by the capacity of the freeway and arterials during that time. If more people want to travel during the peak than can be accommodated by the free-flow capacity of the highway facilities, then the capacity is adjusted downward to reflect the congested conditions. People who prefer the peak, but cannot travel then, are assigned to the shoulders and the model assigns a time penalty to them to reflect the fact that they have to leave earlier than they wish. The length of the time penalty depends on the comparison of demand and capacity in the shoulder. The method is described more fully in the technical report.

Once the model assigns the proper number of trips to the peak hour, the process is repeated for the shoulders. The model adjusts the assignments of the peak to the shoulders according to the capacities. If any trips are left over, the model assumes that those people travel outside of the peak three hours and assigns an appropriate time penalty to them.

### Computation of Speeds and Travel Times

The next steps in the model are relatively straightforward. The model computes speeds for general lanes and HOV

lanes on freeways and for the arterials according to speed-flow curves described in the technical report for this project. From these speeds and the access times used in the model, the total travel times for each mode are calculated.

At this point in the model, total travel times are available and the model uses an algorithm (described in the technical report) to determine if the traffic has been optimally distributed between the freeway and the arterials. If it has, the model computes total costs. If not, all steps are repeated.

### Cost Computation

The model computes time costs using the base case for the value of time and adds these to other associated daily costs. Vehicle operating costs are dependent on travel speeds. The model accounts for the extra operating costs of automobiles and vans due to congestion by adding a percentage (determined by an elasticity) to the costs for each percentage decrease in average travel speed. Transit operating costs take travel speed into account using a cost model, developed at Metro, that treats hours, miles and capital investment costs separately (2). The other daily cost included is parking cost, according to the mode of travel.

For each alternative, daily costs are computed by multiplying the morning peak period cost by an appropriate factor representing the use of lanes in each direction during each peak period. Annual costs are computed by multiplying daily costs by 250. Using straight line interpolation, annual costs for each of the years between 1985 and 2005 are computed and discounted at the appropriate discount rate. Total lifetime costs for each alternative include construction costs, annual maintenance costs and (in the case of the HOV lanes) enforcement costs.

The model treats agency costs, such as construction, maintenance, enforcement and transit operations, separately from costs borne by the traveler (referred to hereafter as "personal" costs). HOV lane alternatives generally cost agencies more than the other two alternatives. The agency cost differences are the "cost" part of the "marginal benefit/cost ratio." The net savings in personal costs (if any) are the benefits in the ratio. The "marginal net present value" simply adds all costs and benefits together, regardless of whether they are agency or personal costs.

### DATA COLLECTION AND ASSUMPTIONS

The simplified approach to freeway modeling and benefit-cost analysis employed in this study precluded the neces-

sity to collect large amounts of data through household or traffic surveys. To the extent possible, the study used existing data or made assumptions that could be tested. This section describes the data that were used and the assumptions that were made in order to complete the analysis. In addition, the section describes the ranges of values that were tested in the sensitivity analysis.

### Person-trips

One of the main determinants of the degree of congestion in a corridor is the number of people traveling through that corridor. Traffic statistics can be used to estimate the number of vehicles on the road, but information on the average occupancy of the vehicles is less well known than the number of vehicles. Current estimates of person-trips are probably within 10 percent of the actual person-trips on the road. However, estimates of person-trips twenty years from now are less certain. Many things could affect those estimates. One unknown factor is the extent to which employers will continue to locate in the suburbs. The number of households and the average number of people in them is also unknown. For these reasons and others, it is very difficult to predict future person-trips in any given corridor.

In order to start with values that were consistent with each other and with other planning efforts in the region, person-trips in each of the three corridors under consideration were obtained from the PSCOG for 1985 and 2000. These estimates are currently used for most transportation planning in the region. Table 3 shows the estimated person-trips for the peak three-hour period for the three corridors under consideration for 1985 and 2000 (3). The 1985 numbers are probably accurate to within 10 percent. The growth rates to 2000 may vary by 25 percent.

For the purposes of this analysis, all three alternatives were assumed to have the same demand. The forecasts were based on the continued existence of HOV lanes that

Table 3. Three-Hour Peak Period Person Trip Demand by Corridor

Location	Year	
	1985	2000
I-5 (just north of Northgate)	45,100	54,800
SR520 (just east of Evergreen Pt. Brdg.)	17,200	21,300
I-405 (just south of I-90)	13,900	15,900

were already in place. Therefore, assuming that demand would be the same for the "do nothing" and "add a general lane" alternatives was not entirely accurate. Because of differences in capacity, the demand would probably have been lower for "do nothing" and higher for "add a general lane" alternatives if capacity had been taken into account. Even though these differences would probably have existed, this study examined the relative efficiency of each alternative in dealing with the same levels of demand.

### Number of HOVs

The number of HOVs for the "do nothing" and "add general lane" cases were assumed to be the same. The number of HOVs in the "add HOV lane" case was derived from the methodology developed by the Charles Rivers Associates (referred to hereafter as the "Parody model") (4). This method analyzed the impacts of 16 HOV lane projects and developed a simple methodology to predict

shifts to HOVs based on the average of these 16 cases. The method was validated on the HOV lanes on I-5 and the prediction of HOVs was found to be within 5 percent of the actual value observed after 20 months of operation.

The volumes of carpools and vanpools were based on current observations on the three facilities being studied. For I-5 and SR520, the current volumes were assumed to be in the "add an HOV lane" alternative. The volumes for the other two alternatives in 1985 were derived by determining the volumes necessary to produce the required volumes in the "add an HOV lane" alternative according to the Parody model. Year 2000 volumes for the first two alternatives were factored from the 1985 volumes proportionally with the increase in total person trips. Year 2000 volumes for the "add an HOV lane" alternative were computed using the Parody model. On I-405, current carpool and vanpool volumes were used for the "do nothing" and "add a general lane" alternatives, since the

Table 4. Peak Period HOV Volumes

Location	Mode	Alternative					
		Do nothing		Add a general lane		Add an HOV lane	
		Year		Year		Year	
		1985	2000	1985	2000	1985	2000
I-5	2 person carpools	4,713	5,727	4,713	5,727	4,713	5,727
	3+ person carpools	317	385	313	385	458	603
	van pools	24	29	24	29	35	45
	buses	90	104	90	104	103	119
SR520	2 person carpools	900	1,115	900	1,115	900	1,115
	3+ person carpools	293	362	293	362	405	579
	van pools	7	9	7	9	10	14
	buses	87	63	87	63	102	72
I-405	2 person carpools	542	620	542	620	838	1,005
	3+ person carpools	207	237	207	237	320	384
	van pools	11	13	11	13	17	21
	buses	211	25	211	25	21	25

HOV lanes had not been in place for long enough to attract much new HOV usage. They were also increased for the year 2000 by using the Parody model.

The numbers of buses for the three facilities were based on actual counts for 1985 and on numbers developed for the Multi-Corridor planning effort recently completed by Metro (5). Table 4 shows all of the volumes used for carpools, vanpools and buses in the three alternatives. There was some uncertainty in all the values used for these elements of the model, especially in the forecasts. However, the reader should note that these were only base values and that one of the objectives of the study was to test the importance of the accuracy of the assumptions. In the absence of good data on HOV volumes, the analysis could still be conducted. In the sensitivity analysis, carpool and vanpool volumes varying by 15 percent for the non-HOV lane alternatives and 30 percent for the HOV lane alternative were tested.

### Percent Preferring Peak

One of the factors that this model takes into account is that when capacity is limited, some people may not be able to travel when they want. For instance, in the morning peak, they may have to leave early in order to guarantee that they get to work on time. On the other hand, if they are able, they may shift their working hours so that they do not have to deal with congested traffic conditions. In either case, they may have to travel during times when they would rather not. In order to account for this, the model computes a time penalty for travelers who are displaced out of the peak hour or out of the shoulder of the peak.

In order to calculate the number of people that are displaced in this way, the model employs an assumption about the percentage of people who would prefer (all other things being equal) to travel in the peak hour. The model further assumes that all people represented by the person-trips in the peak period (three hours long) would prefer to travel during that period. Anyone displaced outside the peak three hours also is assigned a time penalty.

The percentage of people preferring the peak was derived from current actual travel choices. Traffic statistics showed that, on I-5 north, about 38 percent of the traffic during the peak three hours occurred during the peak hour. Presumably, congestion had displaced some people out of the peak hour who would have preferred to be traveling during that time. In addition, vehicle occupancy was greater during the peak hour than in the shoulders of the peak. Since the model deals with person-trips, the relevant data point was the percentage of people traveling in the peak hour. As a base value, the study employed 45 percent as the percentage of people preferring to travel

during the peak hour. A range of 38 percent to 55 percent was tested in the sensitivity analysis.

### Capacity

The capacities for the highway facilities in the three corridors under study had important implications both for the number of people who could travel when they wanted to and the speeds at which they could travel. Three issues were involved in estimating capacities. One was the capacity of a lane in any facility and the second was the number of lanes assumed to represent the corridor's capacity. The third was the relationship between capacity and speed.

The base value for capacity on the freeways was taken from Rutherford and Wellander's study of park-and-ride lots (6). The maximum capacity in that study was 1,873 vehicles per hour per lane. For arterials, the estimate varied between 500 and 700 vehicles per hour per lane. Arterial capacities vary widely according to configurations, number of stop lights and the like. The values used for this study were based on data for urban arterials derived from the most recent version of the Highway Capacity Manual (7). The sensitivity analysis tested a range of 10 percent for freeway capacity and 15 percent for arterial capacity.

The second issue was the number of lanes to include in the analysis. For freeways, the number was obvious. However, since this analysis was at the corridor level, some value for the capacity of parallel arterials was required. The I-5 corridor had seven parallel arterials with a total of 17 lanes that were included in the PSCOG's estimates of person-trips. Even though no major parallel arterials existed in the SR520 and I-405 corridors, some people did travel on side streets to avoid congestion. In order to account for this, the model used the equivalent of one lane of capacity on parallel arterials for those corridors.

The third factor related to capacity was the speed-flow relationship. Again, this study borrowed from the Rutherford and Wellander study and used the same speed-flow curves. The curves were generalized so that assumptions concerning maximum capacity, minimum speed and maximum speed could be tested to see if they influenced the outcome of the analysis. Details of the relationship between flow and speed may be found in the technical report for this study.

### Length

The length of the facilities was fairly precisely known. However, since the parallel arterial capacity was considered in the analysis, and since parallel routes were not

exactly equivalent to the freeway routes, the model tested the value used for the length of the HOV lanes. Length of HOV lanes was a surrogate for inclusion of the exact paths that arterials took and their influence on the total travel time and lengths experienced by people traveling in the corridors. The length of each HOV lane was assumed to be within 10 percent of the equivalent length of the facility when the parallel arterials were taken into account.

### Access Times

The travel cost model has to account for travel time to the facility which contains the HOV lanes in order to fully analyze the differences among alternatives. Average access times to the freeway corridor were used to compute these costs. A distinction was made among different modes. The model employs a base value for access time for all travelers to the freeway segment that contains the HOV lane and adds some increment to account for the different amounts of time carpools or vanpools take to pick up people or for people to reach a bus stop and wait for the bus. The model also allows a value for access time that is shorter for carpools and vanpools when ramp metering is present to be tested.

The model makes no distinction among the various ways to access a particular mode. For instance, the model does not distinguish between walking to a bus stop or driving to a park and ride lot. However, by varying the access time for the bus, different weighting schemes for access could be tested with the model.

Average access times were derived from the PSCOG's travel forecasts for the region and are shown in Table 5 (3). The overall access time was probably within about 15 percent of the actual. The differential access times for the HOVs were assumed to be accurate within three minutes. All of these extremes were tested in the sensitivity analysis using the cost model.

Table 5. Average Access Time

Mode	(minutes)
SOV	11.5
Carpool	12.2
Vanpool	13.5
Bus	21.8

Table 6. Average Trip Length

Mode	Length (miles)	
	1985	2000
All Modes	10	10
SOV	9.6 - 10.0	11.7 - 12.0
2 Person Carpool	12	14
3 Person Carpool	13	14
Vanpool	20	22
Bus	12	12

### Total Trip Length

Just as access times differ by mode, the total length of the trip also has an impact on the costs. On the average, vanpool trips are longer than all other trips. Carpool trips tend to be somewhat shorter, but not as short as bus trips that use the freeway corridors. Trips in SOVs on the freeway tend to be the shortest.

The model assumes that the average trip length for all trips remains the same. When there is a shift in mode, for example from SOVs to vanpools, the model keeps the average trip the same by computing a new (shorter) average trip length for SOVs when additional vanpool trips are anticipated. This takes into account the fact that the additional vanpool trips probably take the place of the longest SOV trips.

Base values for trip lengths, shown in Table 6, were derived from the PSCOG's travel forecasts (3). The sensitivity analysis tested values 10 percent higher and lower than these.

### Minimum and Maximum Speeds

The minimum and maximum speeds allowed by the model affect the way the model calculates effective capacities of the facilities and the average speeds under various conditions. The minimum speeds on freeways and arterials determine the point at which travelers shift their time of travel rather than suffer the effects of greater congestion. The base values for the model are 25 mph on freeways and 12 mph on arterials. Raising the minimums would be

equivalent to assuming that more people travel at times they do not want to, but that average speeds are faster. Reducing the minimums would have the opposite effect. In other words, changing the value results in effects that cancel each other out to some extent. For the purposes of this study, the model tested values that were 5 mph higher or lower than the base values for freeway lanes and 3 mph higher or lower for arterial lanes.

Maximum speeds affect the shape of the speed-flow curve. In general, raising the maximum speed raises the average speed under any condition. However, since the model uses the maximum speed as the base upon which to assess the impact of congestion on operating costs (see the next section), raising the maximum speed also results in higher auto and van operating costs. Changing the value results in effects that tend to cancel each other out, just as with minimum speeds. The base values for this study were 58 mph for freeways and 25 mph for arterials. The sensitivity analysis tested the impact of changing these by 5 mph in either direction for freeway lanes and 3 mph for arterial lanes.

The model also allows the impact of varying maximum speeds on HOV lanes to be tested. For inside HOV lanes, the base value was the same as for general traffic lanes. For outside HOV lanes, such as on SR520, 45 miles per hour was used. Another factor that was tested was the maximum difference that can exist between the HOV lane and an adjacent general traffic lane. For inside HOV lanes, the base value was a 20 mph maximum differential. For outside HOV lanes, 15 mph was used. The sensitivity analysis explored changing each of these values by 5 mph.

## Vehicle Operating Costs

Vehicle operating costs were an important component of the total travel costs used in this evaluation. They were important since each alternative had a different mix of vehicles that traveled at different speeds. Three types of vehicle operating costs were included. Auto operating costs were assumed to be the same, regardless of the number of people in the vehicle. Van operating costs and bus operating costs were the other two categories of costs.

The base value for auto operating costs was taken from research done by the American Automobile Association (AAA) (8). The figure for the base year was \$0.235 per mile for the entire United States, since the AAA does not compute regional costs. The number covered all operating costs, including depreciation and insurance. The cost of insurance was used to represent the cost of accidents. The same value was used for the year 2000, since the model employs current dollar estimates for all costs. The cost of fuel will probably be relatively higher in 2000 than it is

now (adjusted for inflation). However, that factor may be offset by the use of more fuel efficient cars. The sensitivity analysis examined the impacts of errors of up to 10 percent in this value.

Van operating costs were obtained from Seattle Metro. The operating cost (exclusive of depreciation) estimated by Metro was \$0.304 per mile. Assuming that the vans used for vanpooling had a five year life expectancy, and that the original cost was \$10,000, the depreciation cost worked out to just over \$0.11 per mile (132 Metro vans operated for about 2.34 million miles last year.). The total van operating cost, therefore, was estimated to be \$0.42 per mile. The sensitivity analysis examined the same range of values for van operating costs as it did for autos.

Operating costs are relatively higher when vehicles are operating in congested conditions. In stop and go traffic, fuel efficiency decreases and wear and tear on the brakes, drive train and engine are more pronounced. In order to account for this, the model increases operating costs proportionally with decreases in travel speeds resulting from congestion by employing an elasticity for operating costs with respect to speed. The base value used in this study was 0.5 (6). In other words, for every 1 percent the average speed went down, the average operating cost for autos and vans increased by 0.5 percent. In the sensitivity analysis, values varying from 0.25 to 0.75 for this factor were tested.

Bus operating costs were derived from a cost model developed at Seattle Metro (2). A three-part formula was used to compute bus operating costs. The model uses costs that depend on miles traveled, hours in operation and number of peak trips. The Rutherford and Wellander study employed the same methodology. The three parts of the formula were updated for 1985. The costs per mile, hour and peak trip were \$1.31, \$24.83 and \$82.17, respectively. By treating hourly and mileage costs separately, the total operating cost responded to changes in congestion. In the sensitivity analysis, values of up to 10 percent greater or less than these figures were tested.

## Bus Fare

Agency costs for operating buses are partly offset by costs born by the travelers. The base value for bus fare was \$0.80, about half-way between the current peak-hour fares for one-zone and two-zone trips. Metro has a policy of raising fares only to keep up with inflation. Therefore, the same value was used for the year 2000 as for the year 1985. The sensitivity analysis explored the impact of being off by 10 percent in this factor.

## Parking Costs

The model uses different costs for carpool, SOV and vanpool parking. The costs were derived from the PSCOG's transportation models and were assumed not to change between 1985 and the year 2000 (in real terms) (3). The average parking cost in the Seattle CBD was \$3.71 for SOVs and \$3.00 for carpools. Vanpools generally had free parking. Differences as great as 20 percent higher or lower than these figures were explored in the sensitivity analysis.

## Construction Cost

The cost of constructing HOV facilities was the major outlay to consider in this analysis of cost effectiveness. Construction costs for the three HOV lane facilities were provided by the Washington State Department of Transportation (WSDOT). The costs included both construction and design contracts. Each contract necessary to construct the projects was converted to 1985 dollars using the construction index published in the Engineering News Record (9).

Actual figures were used to represent the cost of construction for the "add an HOV lane" alternative. In order to estimate the costs for construction of the "add a general lane" alternative, assumptions were required. For all three facilities, it was assumed that the cost of constructing an extra lane would be 10 percent less than constructing an HOV lane, since signage would not be required and design

costs would be less. Note that on SR520 the shoulder would not have been converted to a general traffic lane. The cost of a new lane would have been much higher than the cost for converting the shoulder to an HOV lane. However, this analysis assumed that SR520's shoulder could be used as a general traffic lane but that it was equivalent to 30 percent of an additional lane.

Table 7 shows the construction and design costs for the three projects, along with totals converted to 1985 dollars. To test the sensitivity of the value for extra costs for HOV lanes, the extra percentage assigned for the HOV lanes was varied between 5 percent and 20 percent of the total costs in the sensitivity analysis.

## Maintenance Costs

Although maintenance costs are an important consideration in computing the cost for adding a lane to a freeway, additional costs that are incurred due to the lane are difficult to determine. It is impossible to assign maintenance costs to a particular lane on the freeway and WSDOT does not maintain records by lane. Over a long period, it should be possible to detect the impact of adding a lane. However, not enough historical data existed to detect changes in maintenance costs that occurred when lanes were added to the facilities under study.

Some argue that because of economies of scale, an additional lane does not add proportionally to the cost of maintaining all the lanes on a freeway. On the other hand,

Table 7. Construction Design Costs (converted costs in parentheses)

Project	Year							Total (1985 \$'s)
	79	80	81	82	83	84	85	
I-5				7316 (7769)	250 (256)		2098 (2098)	10122
I-405						10984 (11074)		11074
SR520	625 (840)			919 (976)	790 (808)			2624
Construction Index	3129.10	3381.62	3725.55	3960.49	4109.53	4171.29	4205.45	
Conversion Factor to 1985 \$'s	1.3440	1.2436	1.1288	1.0619	1.0233	1.0082	1.0000	

an additional lane can impose even greater costs than the proportional increase in lanes. One example of this phenomenon is the higher cost of removing snow from a three lane than from a four lane freeway. Crews have to move more snow over a greater distance and the effect compounds the costs. HOV lanes that take a shoulder also can cause extra costs since the shoulder is not available for daytime maintenance crews, necessitating their payment at overtime rates for maintenance activities during the night.

During the course of this study, no final conclusions were reached regarding the issue of extra costs due to additional lanes for general traffic or for HOVs. Since the arguments for and against distributing costs equally over all lanes cancel each other out, the model uses a cost based on the average lane-mile cost of maintenance for all urban freeway lanes and an additional 10 percent cost for the maintenance of HOV lanes compared with an extra general lane.

Maintenance costs vary from place to place depending on the number of bridges and underpasses, the condition of the shoulders, the land use adjacent to the freeway, the type of pavement and highway geometrics. WSDOT does not keep maintenance records by small enough segments to isolate the total maintenance costs where HOV lanes exist. Therefore, the model used a value of \$4,000 per lane-mile per year for all lanes under consideration, which was derived from the Rutherford and Wellander study (6). Because of the uncertainty involved in using this figure, values as low as \$1,000 and as high as \$10,000 were tested in the sensitivity analysis.

## Enforcement Costs

HOV lanes require extra traffic enforcement to insure that they continue operating as HOV lanes. The amount of investment determines the extent to which the HOV lane requirements are observed, and, therefore, how successful the HOV lanes are. The investment in enforcement is a policy issue, and it is difficult to specify exactly how much enforcement should cost.

The Washington State Patrol (WSP) had recently received a demonstration grant for HOV lane enforcement. Although the new enforcement operation was not yet in place, an estimate of the extra cost needed to enforce HOV lanes was obtained from this grant. The grant provided for six extra troopers and one sergeant to supervise them. They would be expected to enforce HOV provisions on all HOV lanes in the region. They would, of course, occasionally be called to help on other matters. However, since other officers would also occasionally help with the enforcement of HOV lanes, the amount required to provide these extra officers was a good estimate of the investment

required to enforce HOV lane operations.

The cost for each officer and required equipment was about \$40,000 per year, for a total of \$280,000 per year. These costs were allocated to each HOV lane based on the length of the facility. The resulting costs were \$105,000, \$115,000, and \$60,000 per year for I-5, I-405 and SR520, respectively. The sensitivity analysis included a range of 25 percent higher and lower than these base values.

## Value of Time

The value of time is critical to the outcome of any transportation economics study. A wide range of values has been used. Some studies use one-half the average hourly wage, some use the minimum wage (10). Others use alternative bases. Research has shown that using a different value for short time differences than for long time differences is appropriate (11). Other research has shown that in-vehicle time should be valued differently than out-of-vehicle time (12).

The advantage of the approach taken in this study was that the sensitivity of the outcome to the value of time could be tested. In order to simplify the model and to avoid controversies over different approaches that may or may not have made a difference in the outcome of the study, the model employed one value for all types of travel or access time involved in the trips being studied and a wide range of values were analyzed. The base value was \$7.00 per hour, which was approximately two-thirds of the average wage for all workers in this region. It is also consistent with the results of research recently conducted in Texas in which speed choice was used to estimate the value of time (13). The range of values tested was from \$3.00 to \$10.00 per hour.

## Discount Rate

The discount rate is a value used to reflect the difference between the value of money today compared with its value in future years. Economic theory contends that a dollar is more valuable now than the same dollar will be in the future, even when inflation is taken into account. This is because a dollar spent today is no longer available, but a dollar invested today probably will result in more dollars being available in the future. The discount rate is used to reflect the potential value of investing a dollar today rather than spending it.

Since most capital decisions involve the question of whether to spend money now or produce later savings, the value of the current investment is discounted by the potential value of the savings in the future. Therefore, the higher the discount rate used, the less cost effective capital

investments appear to be. The federal Office of Management and Budget (OMB) has specified that a value of 10 percent be used in life cycle cost analysis of investments. The average difference between inflation and the prime interest rate in the last 40 years has been about 2 percent. These values were used to bracket the base value for the discount rate of 4 percent.

## CONCLUSION

HOV lanes may be the most cost effective approach to moving people on many congested freeways. It is clear that a prerequisite for cost effectiveness is substantial recurrent congestion. The models developed in this study are easy to use and widely applicable. They are available for use on IBM compatible personal computers and may be used for estimating cost effectiveness of HOV lanes and alternatives to them. They are also useful for quick and easy application of the Parody model for estimating usage of HOV lanes.

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