Evaluation of the Cost-Effectiveness of HOV Lanes

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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 6 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 one factor did not come close to reversing any of the findings; it required extreme values for virtually all of the factors for reversal. It is extremely unlikely that all the elements of the model were distorted in a direction to cause this outcome. The methodology developed for this study was incorporated into an easy-to-use personal 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.

Congestion is a significant and growing problem in virtually all urban freeway systems in the country. Most of the suggested solutions to the problem entail significant political and financial difficulties. Some say that the only way to solve the problem effectively is to construct additional freeways. However, the construction of new freeways can have severe impacts and in many cases may be ineffective and simply produce more of the same congestion problems. In some cases, light rail systems may preserve adequate mobility in the face of severe congestion. Others argue that the introduction of light rail would have a minimal effect on freeway congestion. In any case, funding for high-capital alternatives such as rail or new freeways is not currently available in most areas.

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

PROJECT OBJECTIVES

The objectives of this study were 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. Potential benefits of HOV lanes include 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 a general lane"), and
3. Construction of an additional lane for transit and carpools ("add an HOV lane").

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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 the future, 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. Details of the computer program and other technical aspects of the study may be found in a separate report (*1*).

STUDY 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 summarized 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 the second one. The first measure was the marginal net present value (NPV), which is the difference between the NPV of the third alternative and those of the other two. The NPV is calculated by subtracting the present value of all the costs of an alternative from the present value of all the benefits. If the NPV of the third alternative were found to be larger than that of either of the other two (in other words, if the marginal NPV 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 in benefits can be realized from the construction of HOV lanes than from doing nothing and the extra costs are only $5 million, the marginal cost/benefit ratio is 4. If this measure is greater than 1, for every dollar spent the return is greater than a dollar.

Table 1 shows the cost-effectiveness indicators for the three locations. Because the marginal NPV was positive for all comparisons, the numbers can be thought of as total savings resulting from implementing HOV lanes rather than from 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 6. This means that each extra dollar spent to implement HOV lanes returned at least $6 compared with the other two alternatives.

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 shows the average overall trip time in the year 2000 for each alternative. HOV-lane speeds are always faster than those in the general traffic lane. In addition, on I-5 and SR520, peak-hour speeds in the general traffic lane were higher for the HOV alternative than for 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 caveat here, 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, there would be 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 ridesharing 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. Using extreme values for any of the factors did not come close

TABLE 2 AVERAGE TRIP TIME FOR ALL MODES IN 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

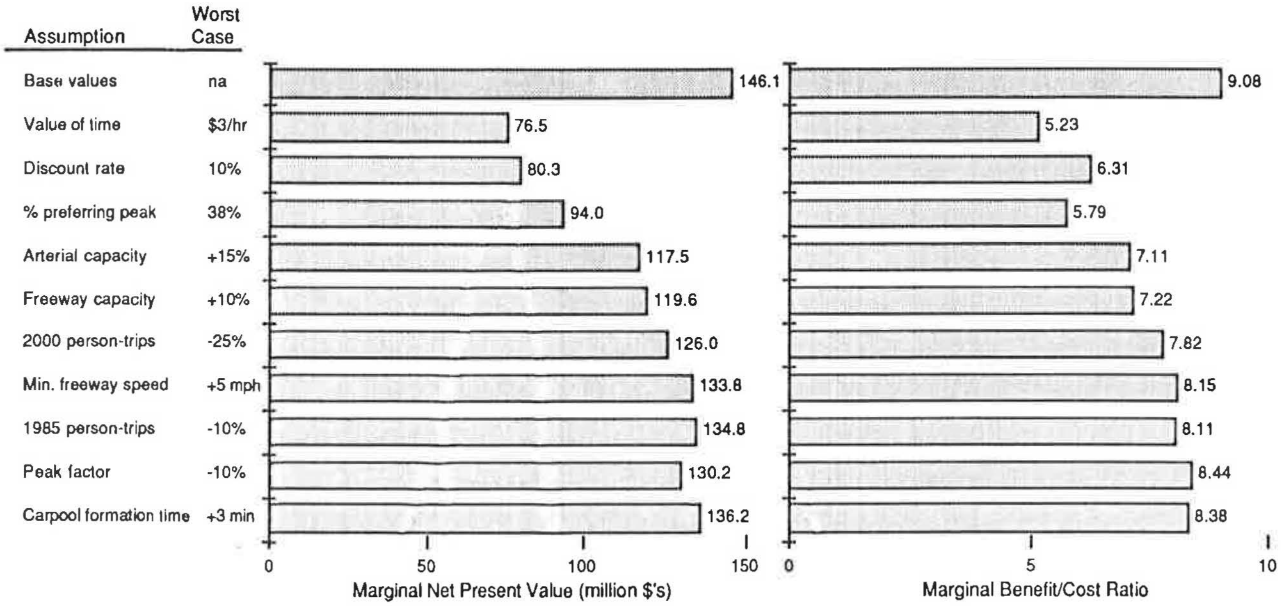

FIGURE 1 Worst cases compared with "do nothing" alternative.

to reversing the basic outcome of the study. The 10 most sensitive factors of the model were determined for each of the alternatives and are shown in Figures 1 and 2, in which the resulting cost-effectiveness measures are shown 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/cost ratio was greater than 5.

All the other factors were related to how congested the corridor is or will become. The less congestion that occurs, the less favorable the HOV lanes are than either 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 increase eventually, errors in these factors only mean that there would be a delay in the time that 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

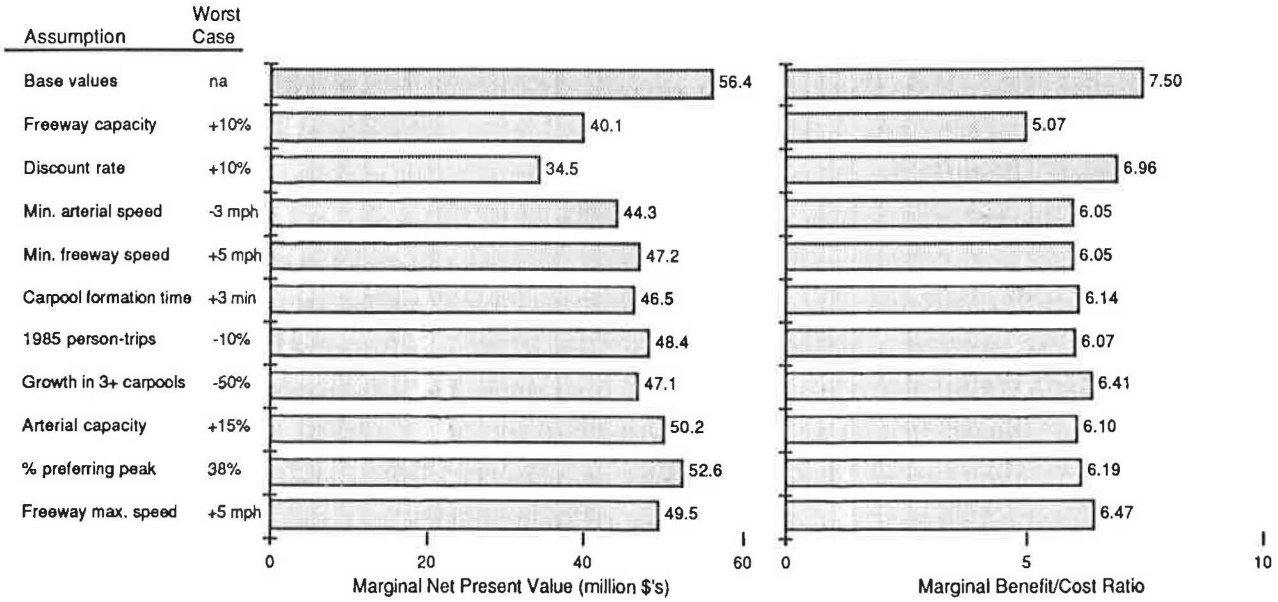

FIGURE 2 Worst cases compared with "add a general lane" alternative.

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 that this many of the base values would be 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 single-occupancy vehicles (SOVs) to carpool, vanpool, 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?

In order to accomplish these multiple goals and to test a number of assumptions, some simplification was necessary. Instead of an attempt to analyze the travel patterns 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.

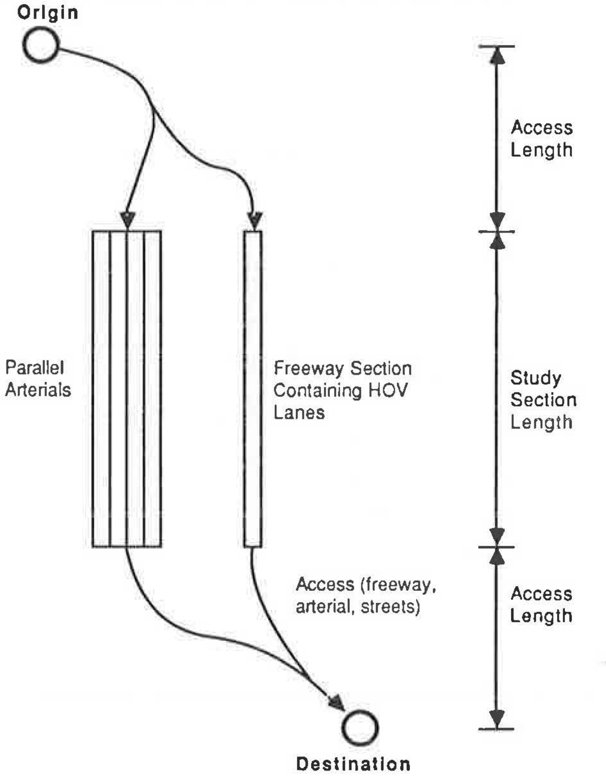

FIGURE 3 Schematic representation of trips using the cost model.

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 lengths on the freeway segment and on 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 choice, 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 2000, resulting in six (3 × 2) scenarios. These years were chosen primarily because person-trip forecasts and other factors for those years were available from the modeling efforts of the Puget Sound Council of Governments (PSCOG). 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 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 asigned to the parallel arterials on the basis of the relative capacity of the arterials. This proportion is adjusted on an iterative basis to minimize the total travel time for all those traveling through the corridor. The optimum total travel time is a legitimate criterion for optimization because it reflects the ability of each traveler to choose on a day-to-day basis between the freeway and the arterial, depending on which one provides faster travel speeds.

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

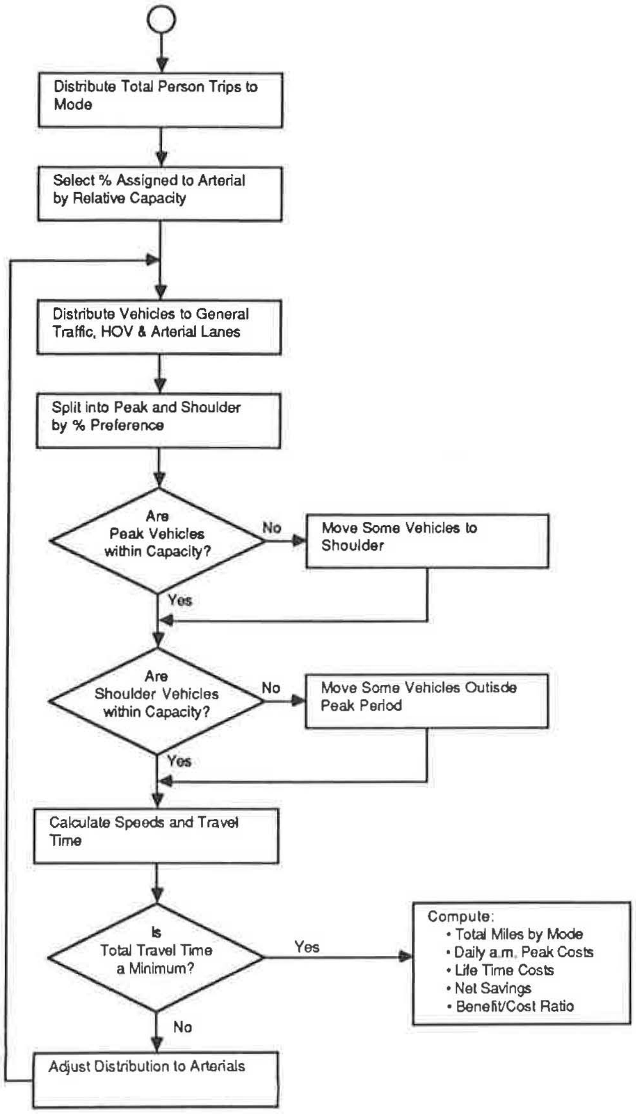

FIGURE 4 Flow diagram for cost model.

other alternatives. If there are no HOV lanes, HOVs are assumed to be distributed in the same manner as all other vehicles.

After the HOVs have been assigned, the model splits the remaining traffic between the freeway and the 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 3 hr, with a 2-hr shoulder split on either side of the peak hour. One important element of the model is the percentage of people who prefer 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 whether those who prefer to travel during the peak hour can be accommodated by the capacity of the freeway and the 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, the capacity is adjusted downward to reflect the congested conditions. Those 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. Once the model has assigned the proper number of trips to the peak hour, the process is repeated for the shoulders.

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 (*1*). 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 whether the traffic has been optimally distributed between the freeway and the arterials. If it has, the model computes total costs. If it has 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 van and automobile operating costs that are attributable 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 by using a cost model, developed at Seattle Metro, that treats hours, miles, and capital investment costs separately (*2*). The other daily cost included is parking, 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) is the benefit part of the ratio. The marginal NPV simply adds all costs and benefits together, regardless of whether they are agency or personal costs.

DATA REQUIREMENTS AND ASSUMPTIONS

The simplified approach to freeway modeling and benefit-cost analysis employed in this study precluded the necessity of collecting large amounts of data through household or traffic surveys. To the extent possible, existing data were used or assumptions that could be tested were made. Data that were used and the assumptions that were made in order to complete the analysis are described in this section. In addition, the ranges of values that were tested in the sensitivity analysis are outlined.

Person-Trips

One of the main determinants of the degree of congestion in a corridor is the number of people traveling through that corridor. Current estimates of person-trips are probably within 10 percent of the actual person-trips. However, estimates of person-trips 20 years from now are less certain.

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 PSCOG for 1985 and 2000 (*3*). These estimates are currently used for most transportation planning in the region. Table 3 shows the estimated person-trips for the peak 3-hr period for the three corridors under consideration for 1985 and 2000. The 1985 data 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.

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

Number of HOVs

The number of HOVs for the "do nothing" case was assumed to be the same as that for the "add a general lane" case. The number of HOVs in the "add an HOV lane" case was derived from the methodology developed by Charles River 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 I-5 HOV lanes, and the prediction of HOVs was found to be within 5 percent of the actual value observed after 20 months of operation.

The volume of carpools and vanpools was 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, because the HOV lanes had not been in place for long enough to attract much new HOV use. They were also increased for 2000 by using the Parody model.

The number of buses for the three facilities was based on actual counts for 1985 and on figures developed for a long-range planning effort recently completed by Seattle Metro (*5*). Table 4 shows the volumes used for carpools, vanpools, and buses for the three alternatives. In the sensitivity analysis, carpool and vanpool volumes varying 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. However, 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. 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 those who are displaced in this way, the model employs an assumption about the percentage who would prefer (all other things being equal) to travel in the peak hour. The model further assumes that all those represented by the person-trips in 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

peak period (3 hr long) would prefer to travel during that period. Anyone displaced outside the peak 3 hr also is assigned a time penalty.

The percentage of those who prefer 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 3 hr 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. Because the model deals with person-trips, the relevant data point was the percentage of those who travel in the peak hour. As a base value, the study employed 45 percent as the percentage of those who prefer to travel during the peak hour. A range of 38 to 55 percent was tested in the sensitivity analysis.

Capacity

The capacity of the highway facilities in the three corridors under study had important implications both for the number who could travel when they wanted to and the speeds at which they could travel. Three issues were involved in estimating capacities:

- The capacity of a lane on any facility,
- The number of lanes assumed to represent the corridor's capacity, and
- 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 configuration, number of stoplights, 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, because 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 estimates of person-trips. Even though no major parallel arterials existed in the SR520 and I-405 corridors, some traveled on side streets to avoid congestion. 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 (*6*), which were generalized so that assumptions concerning maximum capacity, minimum speed, and maximum speed could be tested to see whether they influenced the outcome of the analysis.

Length

The length of the facilities was fairly precisely known. However, because the parallel arterial capacity was considered in the analysis and the parallel routes were not exactly equivalent to the freeway routes, the model tested the value used for length of the HOV lanes, which was a surrogate for inclusion of the exact paths that arterials took and their influence on the total travel time and lengths experienced by those who traveled 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 that 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 taken by carpools or vanpools to pick up passengers or for passengers 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 travel forecasts for the region (*3*):

Mode	*Time (min)*
SOV	11.5
Carpool	12.2
Vanpool	13.5
Bus	21.8

The overall access time was probably within about 15 percent of the actual time. The differential access times for the HOVs were assumed to be accurate within 3 min. All of these extremes were tested in the sensitivity analysis using the cost model.

Total Trip Length

Just as access times differ by mode, the total length of the trip also has an impact on the costs. On 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 were derived from PSCOG travel forecasts (*3*):

	Length (mi)	
Mode	*1985*	*2000*
All	10	10
SOV	9.6–10.0	11.7–12.0
Two-person carpool	12	14
Three-person carpool	13	14
Vanpool	20	22
Bus	12	12

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 in which 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 when 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, because 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 automobile 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 by 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 that for general traffic lanes. For outside HOV lanes, such as that on SR520, 45 mph was used. Another factor 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 because each alternative had a different mix of vehicles that traveled at different speeds. Three types of vehicle operating costs were included. Automobile operating costs were assumed to be the same, regardless of the number of people in the vehicle. Van and bus operating costs were the other two categories.

The base value for automobile 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, because AAA does not compute regional costs. This 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 2000, because 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 impact 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 5-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 was used to examine the same range of values for van operating costs as that for automobiles.

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. 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 decrease in the average speed, the average operating cost for automobiles 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 three-part formula developed at Seattle Metro that 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 borne by the travelers. The base value for bus fare was $0.80, about half of the difference 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 2000 as for 1985. The sensitivity analysis was used to explore 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 transportation models and were assumed not to change between 1985 and 2000 (in real terms) (*3*). The average parking cost in the Seattle central business district 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 *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 that of constructing an HOV lane, because 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

TABLE 5 CONSTRUCTION AND DESIGN COSTS

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	

than the cost of converting the shoulder to an HOV lane. However, this analysis assumed that the shoulder on SR520 could be used as a general traffic lane but that it was equivalent to 30 percent of an additional lane.

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

Maintenance Costs

Although maintenance is an important consideration in computing the cost for adding a lane to a freeway, additional costs that are incurred because of 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. Moreover, 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 increase costs because the shoulder is not available for daytime maintenance crews, which necessitates paying overtime rates for maintenance activities at night.

Because the arguments for and against distributing costs equally over all lanes tend to 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. 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 ensure 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 such facilities are. The investment in enforcement is a policy issue, and it is difficult to specify exactly how much enforcement should cost.

Currently, HOV enforcement costs fall into two categories: (a) the time and equipment used by the Washington State Patrol (WSP) to monitor the lanes and (b) the HERO program, through which citizens are given a telephone number to call and report violators. Drivers identified in this way receive a series of warnings, although no fine is assessed unless the violation has been witnessed by a WSP officer. The costs for this program are shared between Metro and the WSP.

The WSP 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, which provided for six extra troopers and one sergeant to supervise them. These officers will be expected to enforce HOV provisions on all HOV lanes in the region. They will, of course, occasionally be called to help with other police work. However, because other officers will also occasionally help with the enforcement of HOV lanes, the funds required to provide these extra officers constitute a good estimate of the investment required to enforce HOV-lane operations.

The cost for each officer and required equipment was about $40,000 a year, for a total of $280,000 a year. These costs were allocated to each HOV lane on the basis of the length of the facility. The resulting costs were $105,000, $115,000, and $60,000 a year for I-5, I-405, and SR520, respectively. The sensitivity analysis included a range of values 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 and 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 controversy 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 was analyzed. The base value was $7.00 an 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 an hour.

Discount Rate

The discount rate is used to reflect the difference between the value of money today compared with its value in the future. 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 the availability of more dollars in the future. The discount rate is used to reflect the potential value of investing a dollar today rather than spending it.

Because 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 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 use of HOV lanes.

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