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16. Abstract

District offices of the Texas State Department of Highways and Public Transportation have sponsored research into high-occupancy vehicle (HOV) lane cost effectiveness in Houston, Dallas and San Antonion. Many of these projects have utilized the freeway operations simulation capabilities of the FREQ7 computer model as a tool to assist in the cost effectiveness assessment.

This report documents the process used to derive guidelines for estimation of HOV lane project benefit/cost ratios. An extensive radial freeway FREQ7 model data base was combined with an economic analysis of benefits and costs for barrier-separated HOV lane facilities. The data are intended to provide information to highway and transit planners concerning the potential viability of HOV lanes. The guidelines developed offer a means of initially screening freeways to determine whether more detailed and costly HOV feasibility studies are warranted.

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GUIDELINES FOR ESTIMATING THE COST EFFECTIVENESS OF HIGH-OCCUPANCY VEHICLE LANES

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Research Report 339-5

Improving Urban Mobility Through Application of High-Occupancy
Vehicle Priority Treatments
Research Study Number 2-10-85-339

Sponsored by

State Department of Highways and Public Transportation
in Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

November 1985

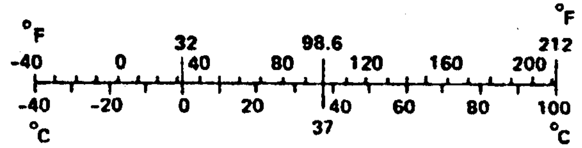
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

ABSTRACT

District offices of the Texas State Department of Highways and Public Transportation have sponsored research into high-occupancy vehicle (HOV) lane cost effectiveness in Houston, Dallas and San Antonio. Many of these projects have utilized the freeway operations simulation capabilities of the FREQ7 computer model as a tool to assist in the cost effectiveness assessment.

This report documents the process used to derive guidelines for estimation of HOV lane project benefit/cost ratios. An extensive radial freeway FREQ7 model data base was combined with an economic analysis of benefits and costs for barrier-separated HOV lane facilities. The data are intended to provide information to highway and transit planners concerning the potential viability of HOV lanes. The guidelines developed offer a means of initially screening freeways to determine whether more detailed and costly HOV feasibility studies are warranted.

Key Words: High-Occupancy Vehicle Facilities, Transit Facility Cost Effectiveness, Transitway, Authorized Vehicle Lane, HOV Lane, Bus Transit, Busway

IMPLEMENTATION STATEMENT

Project 339 is oriented toward assisting the Department in the planning, implementation, operation and evaluation of priority treatment projects. Barrier-separated high-occupancy vehicle (HOV) lanes are included in the regional transit plans of the two largest urban areas (Houston and Dallas) in Texas. As economic and population growth in these and other large Texas cities requires more peak-period person movement capacity, mass transit projects will be considered more frequently in all the larger Texas cities. This report provides information that will allow transit and highway planners to quickly assess the potential viability of HOV lane facilities by using relatively easily obtained data. More detailed and costly HOV studies can then be concentrated in the corridors warranting more extensive evaluation.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas State Department of Highways and Public Transportation. This report does not constitute a standard, specification, or regulation.

SUMMARY

Historically, research into criteria for determining high-occupancy vehicle (HOV) lane cost effectiveness has been directed toward identifying characteristics associated with "successful" HOV lane projects. The general "rules of thumb" derived from that research are: 1) priority lanes should provide a savings of one minute per mile of HOV lane treatment and; 2) a minimum overall savings of five to ten minutes is desirable. Projects that satisfy these criteria have generated approximately twice the increase in vehicle occupancy compared to HOV lanes that do not satisfy those criteria. Peak-hour freeway operating speeds below 25-30 mph (level-of-service E or lower) for a distance of 5 to 10 miles provide the incentive for a significant number of mixed-flow freeway users to alter their trip patterns to utilize a higher occupancy mode. These observations have been used in the HOV lane planning process to determine, at a conceptual level, the ability and appropriateness of an HOV lane to provide a cost effective improvement in peak-period person movement capacity.

HOV lane feasibility studies have not, however, determined the relationships between HOV lane project benefit/cost (B/C) ratios and freeway operating condition. Potential time savings, as described above, is one of several possible indicators that could be utilized in the planning stage to quickly assess HOV lane feasibility at a conceptual planning level. This study, however, also considered the relationship between HOV lane B/C ratios and freeway mainlane volume and queueing information. Demand for the HOV facility was estimated using work trips destined to the central business district (CBD).

The data base for this project consisted of ten calibrated FREQ7 computer freeway simulation models. The Texas Transportation Institute (TTI) utilized this model, developed by the Institute of Transportation Studies at the University of California, Berkeley, for several research projects sponsored by the Texas State Department of Highways and Public Transportation (SDHPT). HOV lane feasibility and freeway operations had been examined on major radial freeways in Houston, Dallas and San Antonio. For this research

effort, the base year models on these facilities were combined with identical traffic growth rates, mode share, and HOV lane cost per mile values for each freeway simulation. Additional models were generated by varying the ramp and mainlane volumes to expand the data base. HOV lane benefit/cost ratios were compared to the possible feasibility indicators.

Base year average daily traffic (ADT) per freeway lane and design year (20 years after the base year) peak-hour HOV lane ridership were found to provide the best combination of: 1) accuracy in estimating B/C ratios; and 2) ease of data collection. These two factors, combined in Equation S-1, had a coefficient of determination (R^2) equal to 0.82.

$$\text{B/C Ratio} = -3.00 + 0.18 \begin{bmatrix} \text{Base Year} \\ \text{ADT per Lane} \\ \text{(1000s)} \end{bmatrix} + 0.57 \begin{bmatrix} \text{Design Year} \\ \text{Peak-Hour HOV Lane} \\ \text{Ridership (1000s)} \end{bmatrix} \qquad \text{Eq. S-1}$$

Figures S-1 and S-2 illustrate the graph of HOV lane B/C ratio versus each factor, along with the "best-fit" (mean) line and 95 percent confidence area. The HOV lane warranting guidelines in Figures S-1 and S-2 provide a means of identifying when more detailed and costly HOV planning analyses may be warranted for a freeway.

The guidelines in Figures S-1 and S-2 were developed using a constant 2.5 percent per year traffic growth rate for the freeway mainlanes. Table S-1 summarizes the effect of varying traffic growth rates on the HOV lane B/C ratios of selected freeways. Varying the annual growth rate by 0.75 percent results in an estimated 20 to 25 percent change in the HOV lane B/C ratio. Increasing the variance to 1.5 percent per year (to 1.0 or 4.0 percent) changes the B/C ratio by 45 to 60 percent. These differences indicate the importance of the growth rate estimate in the HOV lane cost effectiveness analysis.

The capital cost of the HOV lanes and required support facilities (street improvements, park-and-ride lots, etc.) was estimated as $5 million per mile of HOV lane. Locally generated cost estimates may be utilized with Equation S-2.

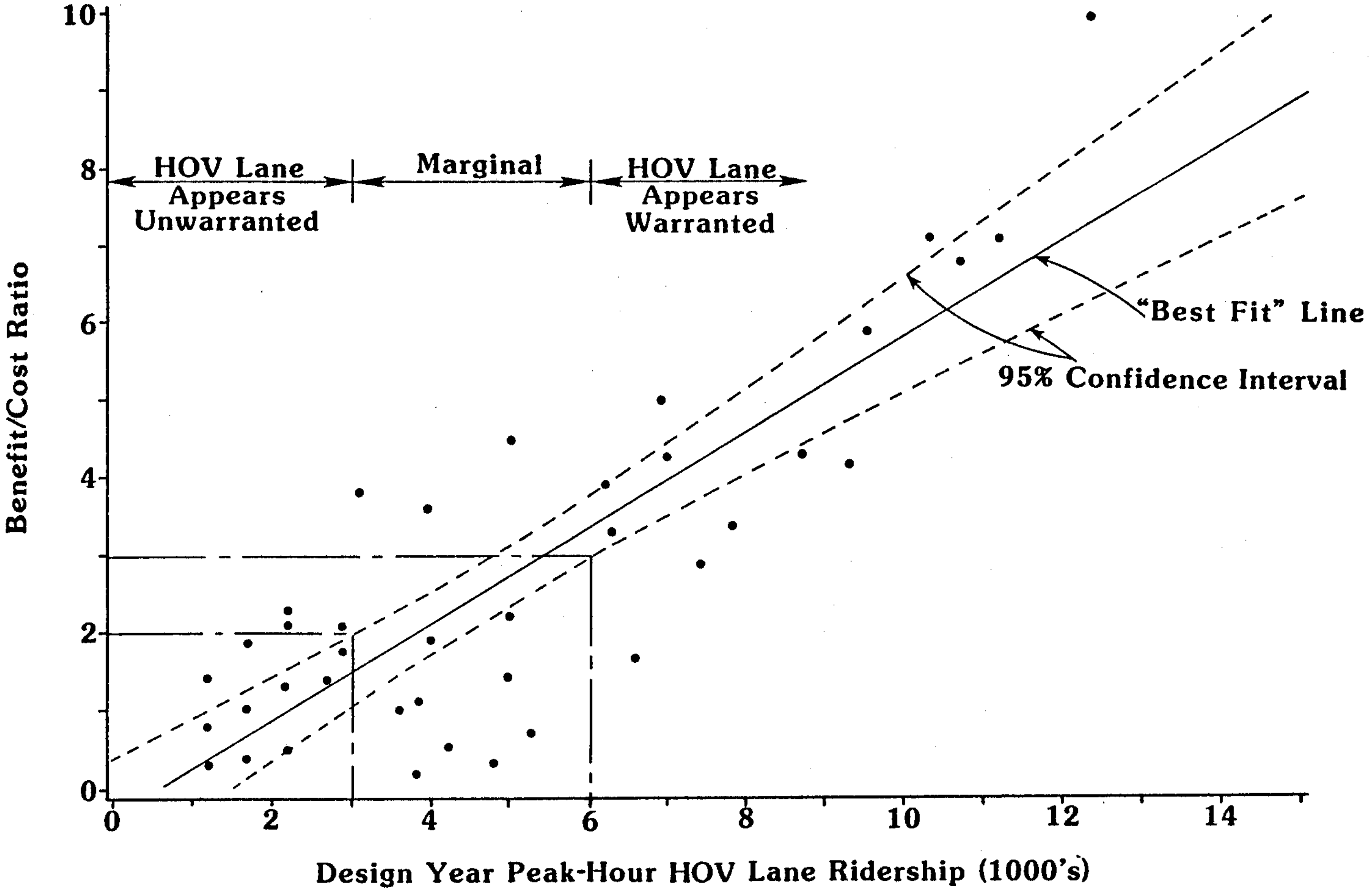

Figure S-1. Relationship Between Design Year Peak-Hour HOV Lane Ridership and the Benefit/Cost Ratio of an HOV Lane Improvement

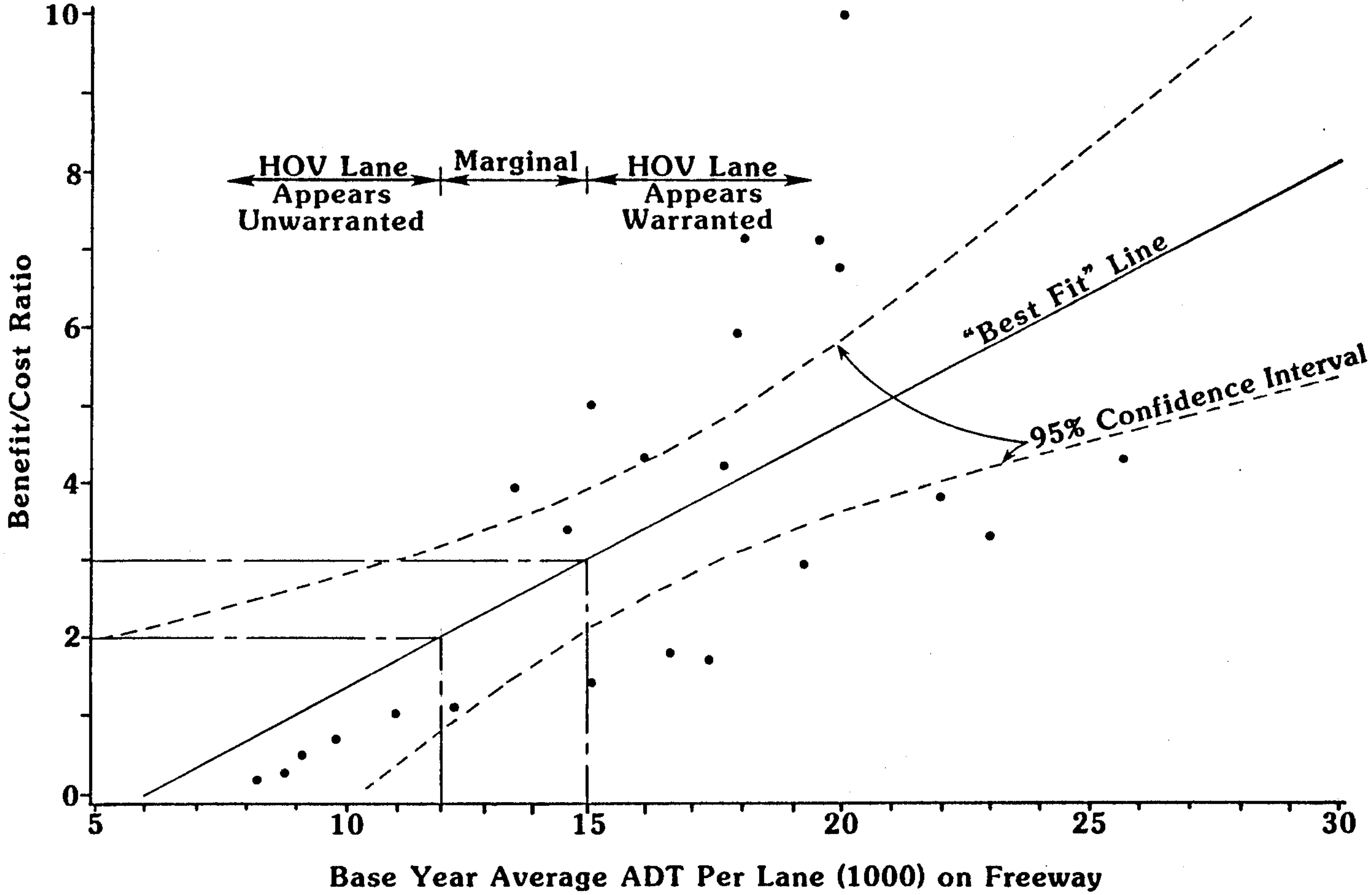

Figure S-2. Relationship Between Year Average Freeway ADT Per Lane and the Benefit/Cost Ratio of an HOV Lane Improvement

$$\text{B/C Ratio For New Capital Cost} = \frac{\text{\$5 Million Per Mile HOV Lane}}{\text{New HOV Lane Cost Per Mile}} \times \text{B/C Ratio From Equation S-1} \qquad \text{Equation S-2}$$

Table S-1. Change in Estimated Benefit/Cost Ratio Due to Change in Annual Growth Rate

Measure	Annual Mixed-Flow Traffic Growth Rate for 20-Year Period (Percent)[1]				
	1.00	1.75	2.50	3.25	4.00
Average B/C Ratio of Six Models with B/C Ratio Ratio Less than 3.0. (for 2.5 percent annual growth)	0.9	1.3	1.7	2.0	2.7
Change from B/C ratio for 2.5 percent annual growth	-45%	-25%	---	+20%	+60%

[1] Annual average HOV lane traffic growth rate is 1.0 percent higher than mixed-flow.

The process described in this report can be utilized by transit and highway planning agencies to assess the need for detailed HOV lane cost effectiveness studies. Estimated benefit/cost ratios are derived from data that are both relatively easy to obtain and illustrative of freeway operating condition. The techniques and guidelines shown in this report provide a means of determining, at the conceptual planning level, whether an HOV lane appears to be an improvement warranting further study for a freeway corridor.

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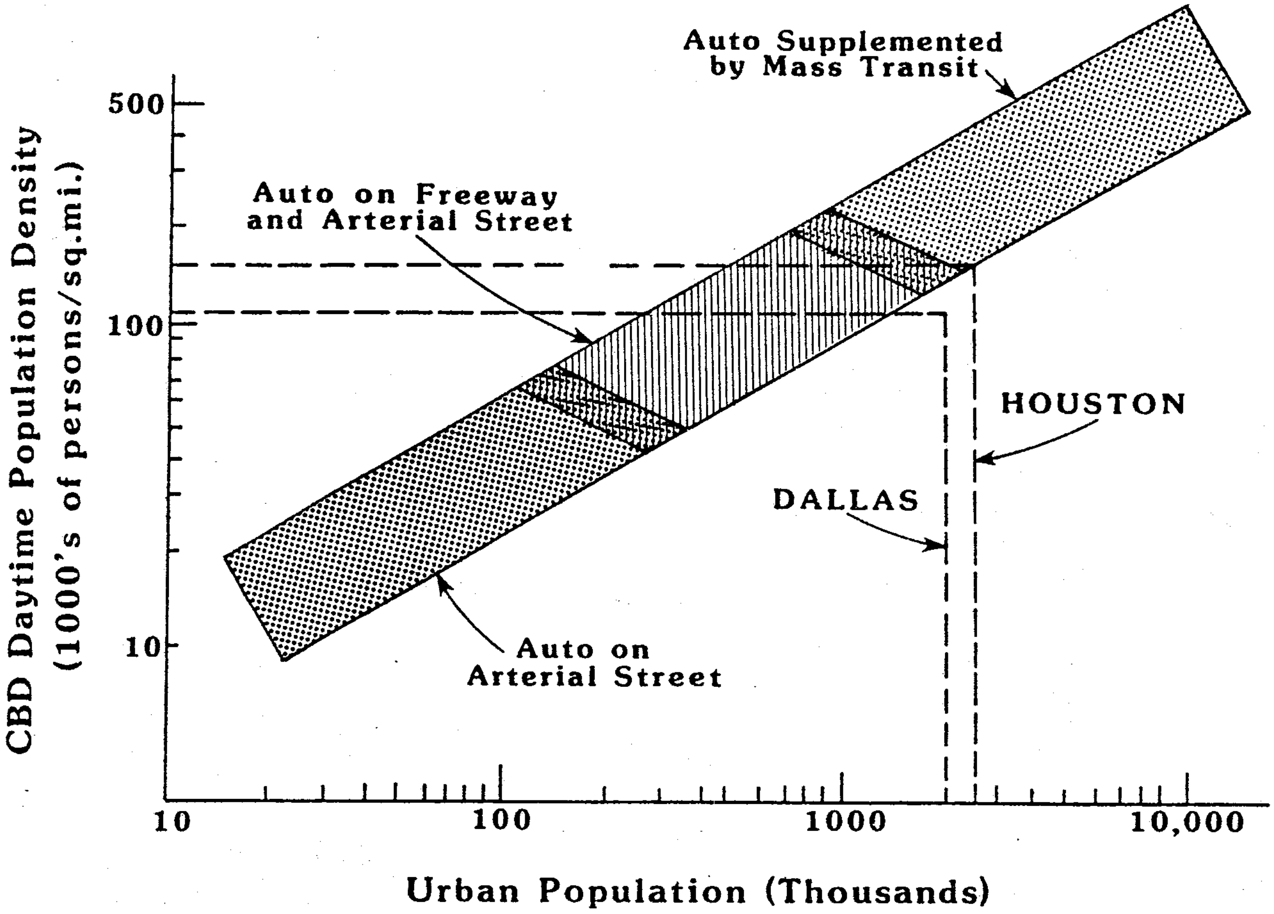
INTRODUCTION

Mass Transportation In Texas

In recent years the residents of several large Texas cities have recognized a need for a more consistent source of transit funding. The creation of independent transit authorities and the dedication of sales tax revenue to those agencies indicate the increasing importance of modes of travel that offer higher occupancy levels than the traditional single-occupant automobile. The traditional social service role of public transportation in Texas is being combined with the peak-period person movement role of mass transportation. In fact, this mass transportation role may become the dominant form of transit in the larger Texas cities.

Park-and-ride service is a widely available form of mass transportation in Texas. It has proven to be a good first step in the phased implementation of higher vehicle occupancy transportation strategies. While park-and-ride is more prevalent in the large, relatively congested cities of Houston, Dallas, San Antonio, Fort Worth and Austin, other cities such as El Paso and Corpus Christi are also utilizing park-and-ride as a supplement to regular route transit service.

As travel corridors become more congested, facilities that provide travel time savings to high-occupancy vehicles (carpools, vanpools and buses) become more cost effective. This situation is analogous to the construction of freeways in an urban area when the arterial street system is too congested to operate efficiently. Figure 1 illustrates this evolutionary nature of person movement facilities. As urban population and peak-period travel demand (e.g., work trips to the central business district (CBD)) increase, transportation infrastructure requirements change. Houston and Dallas are in the range of population and CBD employment density that require some provision of mass transit. Certain corridors in San Antonio, Fort Worth, Austin and El Paso may require priority facilities for mass transit before the year 2000.



Source: "The Influence of Transportation On The Intensity of CBD Development", Compendium of Technical Papers, TexITE Annual Meeting, 1973.

Figure 1. Generalized Relationship Between Transportation and Land Use

The regional fixed guideway transit system plans being developed in Dallas and Houston are mass transit improvement projects that supplement the mixed-flow street and highway system. Barrier-separated HOV lanes (Figure 2) (included in both regional plans) are to be developed in existing freeway corridors to provide peak-period person movement capacity increases and a time-saving alternative to mixed-flow travel.

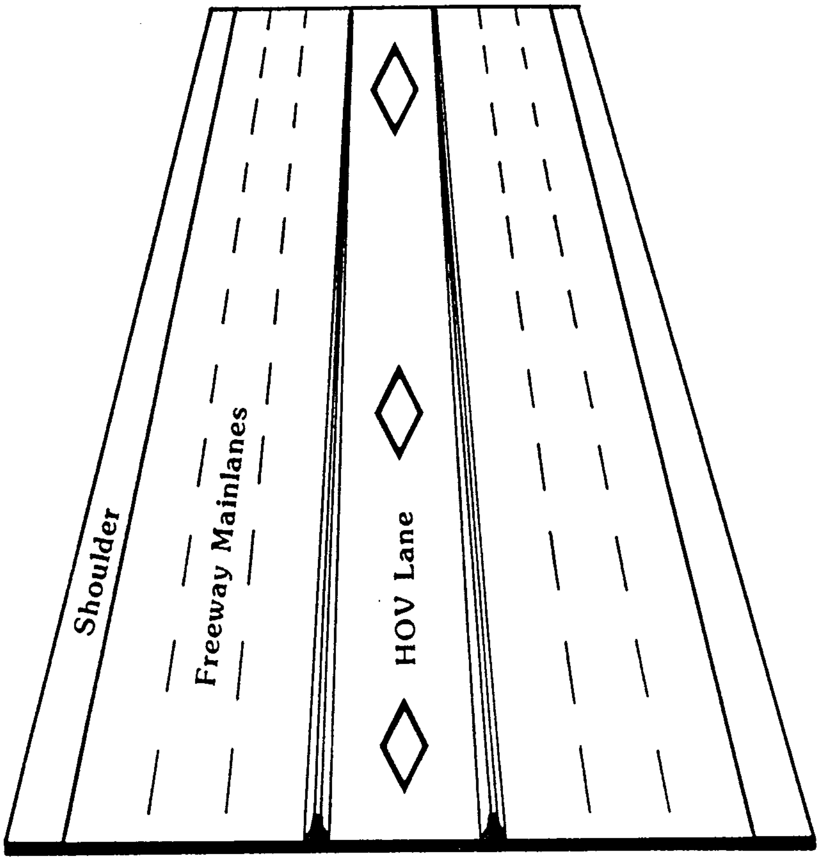


Figure 2. Barrier-Separated High-Occupancy Vehicle Lane in Freeway Median

HOV Lane Planning

The Texas Transportation Institute (TTI), in studies for Districts 12 (Houston), 15 (San Antonio) and 18 (Dallas) of the State Department of Highways and Public Transportation (SDHPT), analyzed the cost effectiveness of HOV lanes on several different freeways. The FREQ7 computer freeway simulation model was used to assist in analyzing freeway mainlane and HOV lane operation. Conceptual HOV lane designs and benefit/cost assessments were utilized to determine the technical and economic feasibility for each potential HOV project. High-occupancy vehicle lanes were found to be cost effective improvements in almost every case; the study freeways were among the most congested in Texas.

The FREQ7 model operating characteristics are covered in subsequent sections of this report, but one of the more important considerations is the cost of model operation. A large amount of detailed traffic volume counts, travel time and speed data are required as model input information. The quantitative output obtained from the modeling procedure is also extensive due to the fact that this program was designed as a freeway operations analysis tool. It is this characteristic that favors the use of FREQ7 rather than some other project analysis models .

Calibrating and utilizing a freeway model to perform an HOV lane analysis is a time-consuming and relatively costly project. This type of modeling effort is more appropriately undertaken when there is a reasonable certainty that the HOV lane will have a high benefit/cost (B/C) ratio. The highly congested freeways examined in previous TTI studies were freeways of this type. Now that many of the more congested freeways have already been analyzed, a question exists as to whether it is necessary to continue to use the FREQ7 model for all other freeway corridors being studied in the State. If possible, findings from previous studies might be used to at least draw some preliminary conclusions regarding HOV feasibility.

A 1979 study for the U.S. Department of Transportation (1)* evaluated operating priority vehicle lanes and concluded that "as a general rule of thumb, the point at which time savings perceived by motorists cause a significant shift to HOVs appears to be when time savings exceed 1 minute per mile." Six of the HOV lane projects analyzed had time savings in excess of one minute per mile of HOV lane; for those projects, average auto occupancy (persons per vehicle) increased 9.8 percent. The five projects that provided less than one minute per mile time savings averaged a 4.4 percent increase in auto occupancy. The implication of this is, if the HOV lane operates at 50-55 mph, the mixed-flow lanes must operate at 25-30 mph (LOS E or lower) for the HOV improvement to generate sufficient time savings to be effective. In

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*Denotes number of references listed at end of report.

addition, some minimum level of time savings, approximately 5 to 10 minutes, appears to be required to initiate the mode shift.

The 1975 NCHRP report on planning and design guidelines for bus facilities on freeways (2) developed warrants for freeway-related priority treatments. Barrier-separated busways were considered possible when at least 40 buses and 1600 passengers would utilize the facility in the design year peak-hour. This study also refers to a minimum time savings of 3 to 5 minutes relative to alternative bus routings. These guidelines, however, do not quantify the relationship between project cost effectiveness and HOV lane ridership, freeway traffic volume, traffic growth or HOV facility cost estimate.

STUDY OBJECTIVES

While general guidelines derived from existing projects delineate the time savings associated with successful priority lane projects, the actual cost effectiveness of HOV lane facilities has not been thoroughly examined. Travel time savings are important in attracting ridership, but the U.S. DOT and NCHRP studies do not quantify the impact of ridership changes on the benefit/cost (B/C) ratio. In addition, the cost side of the benefit/cost equation is important and was not thoroughly considered in the development of previous general guidelines. Existing planning criteria are sufficient for only an initial screening of HOV lane alternatives.

The analysis presented in this report utilizes freeway and HOV lane computer simulation models to relate the freeway characteristics and HOV lane volumes to the B/C ratio of barrier-separated priority lanes located in freeway medians. Quantifying the change in B/C ratio for variations in freeway and HOV lane characteristics produces information desired for conceptual planning level decisions concerning HOV lane feasibility. The guidelines presented in this report provide quantitative values concerning the apparent merits of HOV lanes in a specific corridor. For those corridors where HOV lanes appear warranted, more in-depth evaluations are justified.

FREQ7 FREEWAY SIMULATION ANALYSIS

FREQ7 is the seventh in a series of computer freeway simulation models that were, and are being, developed at the Institute of Transportation Studies (ITS), University of California, Berkeley. The program allows simulation of traffic operations given a set of input parameters. Several different measures of effectiveness (MOEs) are produced which provide the transportation engineer quantitative data to compare various alternative freeway configurations.

Input Requirements

There are two types of input required for the FREQ7 model -- demand characteristics and freeway characteristics. In general, these characteristics require the following data:

- Demand Characteristics -- origin-destination (O-D) patterns, vehicle occupancy levels, distribution of vehicle occupancies

- Freeway Characteristics -- mainlane capacities, mainlane geometrics

Demand Characteristics

Entrance and exit ramp volume counts and freeway mainlane volume counts are used as input information to build a synthetic origin-destination (O-D) trip matrix. The SYNPD2 computer program (also developed at ITS) is an optional subroutine for the FREQ7 model that estimates the number of vehicles traveling to each destination (exit ramp) along the freeway from every origin (entrance ramp). Total entry volumes are apportioned to downstream exit ramps in proportion to the volumes on those exit ramps.

The cost and safety problems associated with postcard or "lights-on" types of freeway origin-destination studies, as contrasted to the relatively simple and accurate SYNPD2 program, has led to the increased use of the synthetic O-D technique for FREQ7 modeling. The freeway modeling conducted by TTI primarily has pertained to the morning peak, inbound freeway operation. SYNPD2, in this application, tends to overestimate short freeway trips. An analysis of FREQ7 MOEs (3), however, has shown that errors of the magnitude found in synthetic O-D tables do not significantly alter values related to freeway operations.

Vehicle mix and vehicle occupancy are also required for freeway mainlane modeling. Proportions of single occupant, double occupant, 3 or more occupant cars and buses in the traffic stream are required for each entrance ramp.

Freeway Characteristics

Freeway characteristics quantify the supply side of the freeway system. The modeled length of mainlane freeway is governed by: 1) a maximum of 40 freeway subsections; or 2) a maximum of 20 input or 20 output locations. A subsection is defined as a point of demand change (entrance or exit ramp) or a geometric change (e.g., lane drop/addition, large gradient change, etc.) The user must also supply (for each subsection) the number of lanes, the mainlane capacity, gradient, curvature, speed/flow curve, ramp characteristics and percentage of trucks. Another limitation of FREQ7 is the maximum 24 time slices, which, when used in 15-minute increments, limits the model length to 6 hours. This is sufficient to encompass freeway operations during a single peak period in the peak direction.

These data needs have been satisfied utilizing recording machine traffic counters, manual mainlane traffic counts, and travel time and speed studies. The traffic counts are recorded at 15-minute increments and the travel time runs are started at 15-minute intervals. Some of the data is generally available from area planning agencies, but the detailed count and travel speed information is usually too expensive for those agencies to collect on a regular basis. Data collection and reduction costs for a 6-hour FREQ7 model have typically been more than $20,000.

Modeling Assumptions

There are certain assumptions that the FREQ7 program makes in order to operate effectively and efficiently. It assumes that freeway operations can be simulated by ignoring any randomness in traffic behavior and the behavior of individual vehicles. The program operating procedure transfers demand downstream instantly at the beginning of each time slice unless demand exceeds capacity. This process greatly reduces computing time and is sufficiently accurate for almost all situations. It does not provide the detailed accounting of individual vehicle movements provided by more microscopic models and required in some traffic engineering analyses.

If demand exceeds capacity in a particular time slice/subsection combination, traffic is stored on upstream entrance ramps or upstream freeway sections. These vehicles became part of the demand for the following time slice and are counted in the travel time delay estimate. The model does not, however, shift the mode of trips or the entry location, and it assumes that traffic demand and roadway capacity remain constant over a time slice.

Freeway HOV Lane Analysis With FREQ7

The input data is used to calibrate the model to existing freeway conditions using the speed and congestion contours derived from the travel time runs. The model information is adjusted to match the observed information by changing subsection capacity (service volume) in the congested areas. The level of precision is well within that of the input data and is consistent with the ultimate use of the FREQ7 model. The TTI FREQ7 analysis procedure compares freeway mainlane operation to freeway and HOV lane operation for the design year (20 years in the future).

The FREQ7 model provides considerable data that permit quantitative comparison of alternatives. The measures of effectiveness (MOEs) included in the output are: 1) vehicle-hours and passenger-hours of travel on the freeway; 2) vehicle-hours and passenger-hours of ramp delay; 3) total vehicle-hours and passenger-hours; 4) total vehicle-miles and passenger-miles; 5) average vehicle speed; and 6) total fuel consumption.

The FREQ7 freeway mainlane model cannot be used to estimate operation of a barrier-separated, one-lane reversible HOV lane. A second model, therefore, must be developed to simulate HOV operation. The HOV trips are removed from the freeway mainlane SYNPD2 matrices and placed into a separate SYNPD2 matrix set for HOV lane traffic. The input values for demand and freeway characteristics are also required in the HOV lane FREQ7 model.

HOV Lane Benefit/Cost Analysis

Measures of effectiveness from the FREQ7 output are utilized in the benefit assessment process. The design year analysis compares the freeway mainlanes to mainlanes with an HOV lane to determine travel savings realized by the freeway/HOV lane project users. The design year freeway model is derived using traffic volume growth rates in the SYNPD2 program. Freeway mainlane and ramp demands are increased and the FREQ7 model is then run using the higher volumes.

The benefit assessment procedure utilized for this report requires that demand be equal for the "freeway-only" and freeway/HOV lane models. This is accomplished by equalizing the passenger-mile value for those models. This is required due to problems in the transfer of trips from the mainlanes to the HOV lane and in the accounting process used with congested mainlane models. Transferring passengers from the mainlane entrance ramps (with spacings approximately every mile) to the HOV lane (with entrances that average 3 to 5 miles apart) results in some discrepancies in the amount of miles traveled on the two different facilities. Freeway models with congested operation at the end of the modeling period (e.g., 12 noon in a 6 a.m. to noon model) do not count those vehicles that cannot be accommodated on the mainlanes. Passenger- and vehicle-miles of travel are, thus, deleted from the mainlanes due to their delayed input to the FREQ7 model.

These problems usually leave the "freeway-only" passenger-miles of travel lower than the freeway/HOV lane combination. The "freeway-only" MOEs for B/C ratio calculation -- passenger-hours of travel and fuel consumption-- are multiplied by the ratio of freeway/HOV lane passenger-miles to "freeway-only" passenger-miles (Equation 1). Demand in the system is, thus, held constant, and "freeway-only" MOEs are increased by a conservative estimate. (According to the speed-flow curve, travel time should increase at a geometric rate rather than simply a linear rate).

$$\underset{\text{MOE}}{\text{Freeway/HOV}} = \underset{\text{MOE}}{\text{"Freeway-Only"}} \times \frac{\text{Freeway/HOV Passenger-Miles}}{\text{"Freeway-Only" Passenger-Miles}} \qquad \text{(Eq. 1)}$$

The benefit/cost (B/C) ratio calculation utilized for this analysis can be expressed mathematically by Equation 2.

$$\text{B/C Ratio} = \frac{B}{(C+M)-S} \qquad \text{(Eq. 2)}$$

Where:

B = Present value of net benefits;
C = Capital cost or initial investment;
M = Present value of maintenance and operating costs; and
S = Present value of salvage value at end of time period.

The numerator of the equation represents the twenty-year benefit cash flow, while the denominator represents the capital cost or investment necessary to construct and operate the facility.

Benefit Estimation Procedure

The benefits to accrue as a result of a freeway improvement project are usually expressed as a reduction in costs to the traveling commuter. The savings in passenger-hours of travel and fuel consumption can be determined directly from the FREQ7 output. Fuel costs were estimated at $1.25 per gallon. Savings in passenger-hours of travel comprise 80 to 90 percent of the total estimated benefit value. This conceptual planning level feasibility analysis does not identify passenger travel time by trip purpose, therefore, an aggregate value was estimated for all trip modes and purposes.

Two techniques were utilized (4, 5) and updated to 1980 using the Consumer Price Index. An estimate of $7.00 per passenger-hour of travel was derived from this process and used for all HOV lane feasibility analyses.

An additional benefit is the reduction in bus operating time. Buses that can utilize the HOV lane may have a much higher average travel speed than vehicles in the freeway mainlanes. This can be a significant portion of the total project benefits and is a direct savings in operating cost to the transit operator. Shorter trip times also mean that each bus may make more round trips and, therefore, decrease the number of buses required to serve the corridor trip demand. The benefit derived from fewer buses to be purchased and maintained is not quantified, but Table 1 illustrates some large transit system operating cost estimates. This study utilized a value of $50.00 per bus operating hour to quantify savings for bus operations on the HOV lanes relative to travel on the freeway mainlanes.

These benefits (passenger travel time, fuel consumption and bus operating time) are determined for the morning peak base and design years using the FREQ7 output. Benefits for the period between those two years are assumed to grow at a constant percentage rate. This benefit assessment results in a somewhat conservative estimate of total project benefits. Benefits from weekend or special event use or accident reduction are not included. In the typical FREQ7 HOV lane analysis the morning peak inbound direction is modeled. The benefits derived from this peak direction analysis are multiplied by 2 to estimate total daily benefits. Evening peak direction volumes are higher and congestion, therefore, worse on almost every freeway. Multiplying the morning benefits by two results in a conservative estimate of total benefits.

The opportunity cost (discount rate) "reflects the scarcity of investment resources relative to investment opportunities" (6). The Office of Management and Budget (OMB) mandates a discount rate of 10 percent to be applied to future benefits and costs. This relatively high value also results in a conservative benefit total.

Table 1. Bus Operating Cost Per Hour For Several Large Transit Systems

Transit System	1982 Bus Operating Cost Per Hour (dollars)
Manhattan and Bronx Surface Transit Operating Authority	$50.81
Orange County (CA) Transit District	49.04
Southern California Rapid Transit District	49.76
Chicago Transit Authority	43.64
Southeastern Pennsylvania Transportation Authority	49.54
Southeastern Michigan Transportation Authority	77.00
Alameda-Contra Costa (CA) Transit	43.62
San Francisco Municipal Railway	45.50
Washington Metropolitan Area Transit Authority	47.46
Dallas Transit System	37.00
Bi-State Development Corporation	44.35
Port Authority of Allegheny County	42.35
Mass Transit Administration - Baltimore	42.89
Denver Regional Transportation District	44.26
Houston METRO	51.68

Source: Reference 7

Cost Estimation Procedure

The costs to be considered in computing the B/C ratio include both capital investment costs and annual maintenance and operating costs. The estimated cost for twenty years of maintaining and operating an HOV facility is represented by "M" in the B/C equation. The capital investment cost is added to the maintenance cost in the denominator of the B/C equation and includes the initial cost of construction. The present value of any salvage value at the end of a project's useful life is subtracted from the total cost.

For the purposes of this investigation, the HOV lane alternatives were all assumed to have a 20-year useful life and zero salvage value as suggested in the OMB Circular. Annual HOV lane operating cost was based on that experienced on the Houston contraflow project and was assumed to be $250,000 per year. Initial construction cost estimates were derived from the single lane, barrier-separated HOV lanes being developed in Houston. HOV lane guideway and interchanges, park-and-ride lots and street improvements are estimated to cost:

- $40 million for 11.5 miles on Katy Freeway ($3.5 million per mile)
- $70 million for 17.6 miles on North Freeway ($4.0 million per mile)
- $80 million for 15.5 miles on Gulf Freeway ($5.2 million per mile)

This study utilized an initial capital construction cost of $5 million per mile of HOV lane.

Actual HOV Lane Project Benefits

The actual benefits (as opposed to those estimated within this report) that will result from an HOV lane improvement are more difficult to quantify in a meaningful manner. In reality, it is unlikely that mainlane congestion will decrease as a result of HOV lane implementation. The real benefit of the HOV lane will be to move more persons in the peak period, thereby supporting more regional economic development at existing levels of freeway congestion. Thus, the primary benefits are more employment opportunities and the ripple effect of those new jobs throughout the regional economy. These benefits may be of an order of magnitude above those that might result from reduced freeway congestion.

However, a means of estimating benefits would be to assume that all the traffic using the HOV lane is diverted from the freeway mainlanes. The resulting reduction in passenger-hours of freeway travel time due to higher operating speeds provides a conservative estimate of potential benefits.

FREQ7 FREEWAY SIMULATION MODELS: EXISTING DATA BASE

The Texas Transportation Institute (TTI) through several different contracts with the Department (SDHPT), has calibrated and utilized FREQ7 simulation models on 10 radial freeways and 3 circumferential freeways in Houston, Dallas and San Antonio. This section summarizes the base year (year in which FREQ model is calibrated) data for each freeway. Subsequent sections detail the changes required, and analysis techniques used, in this project to develop generalized guidelines.

Department Sponsored Computer Modeling Projects

Basic time and distance parameters for the calibrated freeway models are summarized in Table 2. Constraints on the number of freeway subsections that could be handled by one FREQ7 model required the use of more than one model for some freeways. The radial freeways are modeled for morning peak-direction travel from locations upstream of base year, peak-hour congestion, through the congested freeway segments, until the maximum number of subsections is reached. The FREQ7 model operates more accurately if the freeway is uncongested at the endpoints over the entire modeling time period. The freeway segments were chosen to satisfy this constraint whenever possible. The models were developed to analyze priority lane projects, which required an operational model over the entire expected HOV lane length. The freeways in Tables 2 and 3 contain a range in mileage (8 to 24 miles) and width (2 to 5 lanes) illustrating a wide variety of freeway mainlane operating conditions.

The freeways listed in Tables 2 and 3 are among the most congested in Texas and, thus, the individual HOV lane analyses performed by TTI for the Department resulted in relatively high HOV lane project B/C ratios. Data such as traffic volume growth rates, HOV lane ridership, estimated improvement cost, and HOV lane configuration were determined in each analysis and reflect specific considerations. The analysis used in this study, however, utilized consistent estimates for HOV ridership, cost and traffic growth rates that facilitate comparisons of the different base year operating conditions. The major consequence of this action is to fundamentally alter the

Table 2. Freeway Sections and Time Periods Modeled With FREQ7

City and Freeway Type	Model Endpoints	Approximate Distance (miles)	Base Year[1] For Analysis	Direction and Time Period
RADIAL				
Houston				
Southwest (US 59)	West Bellfort to Spur 527	12.7	1981	EB 6:00-Noon
Katy (I-10)	Barker-Cypress to Washington	16.3	1981	EB 6:00-Noon
North (I-45)	Shepherd to I-10	8.9	1982	SB 6:00-Noon
Eastex (US 59)	FM 1960 to I-610	14.8	1981	SB 6:00-Noon
Dallas				
East R.L. Thornton (I-30)	Zion to I-45	15.6	1982	WB 6:00-Noon
North Central (US 75)	Spring Creek to I-635	10.7	1982	SB 6:00-Noon
North Central (US 75)	I-635 to Washington	8.5	1982	SB 6:00-Noon
Stemmons (I-35E)	Denton County to Inwood	15.1	1983	SB 6:00-Noon
Airport (SH 183)	D/FW Airport to Stemmons Fwy. (I-35E)	10.3	1983	EB 6:00-Noon
San Antonio				
I-10 West	FM 1604 to Woodlawn	13.1	1983	EB 6:00-Noon
CIRCUMFERENTIAL				
Houston				
West Loop (I-610)	South Loop to North Loop	8.8	1982	NB & SB 6:00-Noon
West Loop (I-610)	South Loop to North Loop	8.8	1982	NB & SB 3:00-9:00 p.m.
Dallas				
LBJ (I-635)	SH 352 to Luna	24.0	1983	EB & WB 6:00-Noon
San Antonio				
Loop 410 (I-410)	Perrin-Beitel to Culebra	15.7	1983	EB & WB 6:00-Noon
Loop 410 (I-410)	Perrin-Beitel to Culebra	15.7	1983	EB & WB 2:00-8:00 p.m.

[1] Initial year of analysis; year in which FREQ7 model calibrated.

Table 3. FREQ7 Computer Model Peak-Direction Freeway Lane Configuration

Freeway	Section Endpoints	Number[1] of Lanes	Section Length (miles)
RADIAL			
Southwest (US 59)	West Bellfort to Chimney Rock	3	7.9
	Chimney Rock to I-610	4	0.5
	I-610 to Weslayan	5	1.2
	Weslayan to Shepherd	4	1.9
	Shepherd to Spur 527	5	1.2
Katy (I-10)	Barker-Cypress to Wirt	3	12.9
	Wirt to I-610	4	1.9
	I-610 to Washington	5	1.5
North (I-45)	Shepherd to Airline	3	4.9
	Airline to I-10	4	4.0
Eastex (US 59)	FM 1960 to Tidwell	2	12.2
	Tidwell to I-610	3	2.6
East R.L. Thornton (I-30)	Zion to US 80	2	9.4
	US 80 to I-45	4	6.2
North Central (US 75)	Spring Creek Parkway to I-635	2	10.7
North Central (US 75)	I-635 to Mockingbird	2	5.8
	Mockingbird to Washington	3	2.7
Stemmons (I-35E)	Denton County to I-635	3	7.1
	I-635 to Loop 12	4	2.6
	Loop 12 to SH 183	3	4.3
	SH 183 to Inwood	5	1.1
Airport (SH 183)	D/FW Airport to Stemmons Freeway	3	10.3
I-10 West	FM 1604 to I-410	2	7.2
	I-410 to Fredericksburg	3	5.1
	Fredericksburg to Woodlawn	2	0.8
CIRCUMFERENTIAL			
West Loop (I-610)NB	South Loop to I-10	4	7.2
	I-10 to US 290	5	1.6
West Loop (I-610)SB	US 290 to I-10	5	1.6
	I-10 to South Loop	4	7.2
LBJ (I-610)EB	Luna to SH 352	4	24.0
LBJ (I-610)WB	SH 352 to Luna	4	24.0
Loop 410 (I-410)EB	Culebra to Ingram	2	0.9
	Ingram to Perrin-Beitel	3	14.8
Loop 410 (I-410)WB	Perrin-Beitel to Ingram	3	14.8
	Ingram to Culebra	2	0.9

[1] General number of mainlanes; does not reflect auxiliary lanes or configuration for short sections at freeway-to-freeway interchanges.

design year freeway operating characteristics and conclusions concerning HOV lane cost effectiveness. The individual freeway models are not representative of the original analyses performed for the Department; they are more closely related to the base year operating characteristics than the future operation of the actual physical facility. Table 4 lists the labels that are used (instead of the freeway names) in the radial freeway analyses presented subsequently. The individual conceptual design analyses should not be compared to the B/C ratios derived in this study.

Table 4. Freeway Labels Used for B/C Ratio Analysis

Freeway Model[1]	Freeway Label
Southwest (US 59)	A
Katy (I-10)	B
North (I-45)	C
Eastex (US 59)	D
East R.L. Thornton (I-30)	E
North Central, N. Section (US 75)	F
North Central, S. Section (US 75)	G
Stemmons (I-35E)	H
Airport (SH 183)	I
I-10 West	J

[1] See Tables 2 and 3 for freeway model characteristics.

Circumferential Freeway HOV Lanes

While analyses are available for the circumferential freeways and guidelines would facilitate the conceptual design of HOV lane facilities, the available data base (three freeways) is small. The study procedure requires several variables to be analyzed together necessitating numerous data points. The circumferential data base is inadequate for this analysis. In addition, the historical data used for ridership, travel pattern and mode share estimation on radial freeways is not available for circumferential freeways. To date, no major HOV lane operates on a loop freeway and, thus, no test for reasonableness exists for these types of facilities.

Some sections of all three circumferential freeways (West Loop, LBJ and Loop 410) operate similar to traditional radial freeways with a dominant directional trip distribution. HOV lane planning for these freeway segments could utilize the guidelines developed for reversible HOV lanes on radial facilities. When circumferential HOV lane facilities begin operation, an evaluation of the freeway characteristics and development of two-direction priority lane guidelines would be appropriate.

HOV LANE BENEFIT/COST RATIO ANALYSIS PROCEDURE

Several freeway operation and corridor trip pattern characteristics are related to HOV lane cost effectiveness. The primary study objective was to discover which of these factors most accurately predict HOV lane project benefit/cost (B/C) ratios. This section describes the values and procedures utilized in the analysis.

B/C Ratio Analysis Constants

Several input values used in FREQ7 and the B/C ratio calculation were held constant for all freeways to allow comparisons to be made for various freeway operating condition parameters.

HOV Lane Project Life and Cost

As mentioned previously, a typical highway project life of 20 years was used for the HOV lane with no salvage value at the end of that term. A project cost of $5 million per mile of HOV lane was used to calculate the cost of line-haul guideway, interchanges and associated highway, street and transit improvements. The capital cost values in Table 5 are based on construction costs for the one-lane reversible HOV lane projects in Houston.

Traffic Volume Growth Rate

As freeway traffic volumes increase, mainlane delay and potential HOV lane time savings also increase. The average traffic volume growth rate used in the FREQ7 modeling process was held constant for all freeways to eliminate the inconsistencies that develop when two models with the same base year conditions are subjected to two different growth rates. An average growth rate of 2.5 percent per year was used in the general analysis. Subsequent analyses were performed to determine the general relationship between a change in growth rate and B/C ratio.

Table 5. HOV Lane Capital Cost Values Assumed For Analysis

Freeway Label	HOV Lane Length (miles)	HOV Lane Capital Cost ($ million)[1]
A	12.7	63.5
B	13.0	65.0
C	8.9	44.5
D	14.8	74.0
E	12.2	61.0
F	10.7	53.5
G	8.5	42.5
H	15.1	75.5
I	10.3	51.5
J	13.1	65.5

[1] Does not include cost for buses and maintenance facilities

Mode Share and HOV Lane Ridership

The percent of total freeway person movement being carried in high-occupancy vehicles (HOV mode share) is estimated for use in the modeling process. Total morning peak CBD work trips are estimated by multiplying base year downtown employment by the percent of workers present on an average day (95 percent). Freeway work trips serve a sizable portion of the total CBD morning peak trips, with arterial streets serving the remainder. The number of trips entering the CBD from each freeway is estimated using the proportion of the ADT values near the CBD. Equation 3 summarizes this process.

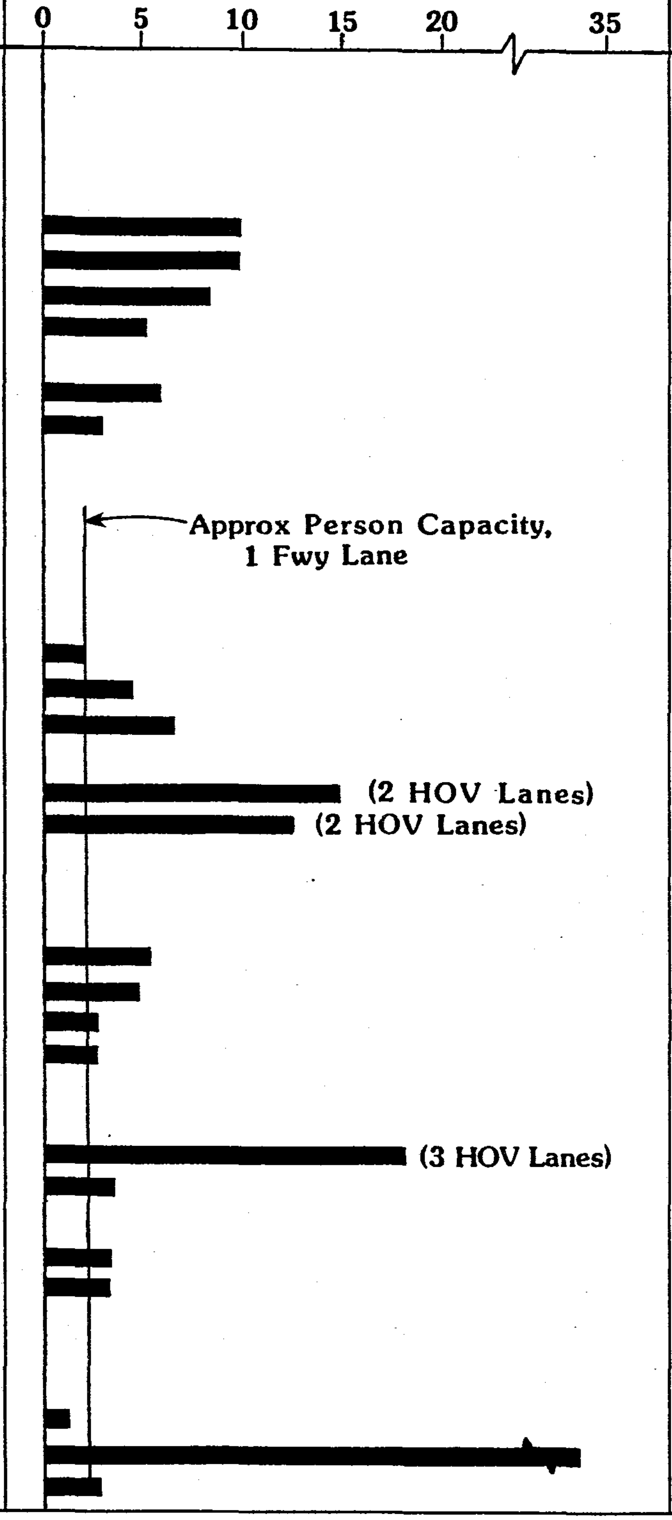
Based on data from the El Monte Busway in Los Angeles and the North Freeway Contraflow Lane in Houston, an average HOV mode share value of 45 percent was used for this analysis. While this value may appear high for typical auto-oriented travel patterns, the time savings that can be generated from an HOV lane, the concentrated nature of CBD employment and the high downtown parking costs combine to shift the typical commute patterns. Study freeway work trips were multiplied by 0.45 to estimate peak-period, CBD-bound HOV lane ridership. Half of this volume was assumed to use the lane in the peak hour, a value also estimated from El Monte and North Freeway. Sixty percent of the ridership was assumed to use buses (50 persons per bus), with 40 percent in vanpools (nine persons per van).

$$\frac{\begin{array}{c}\text{Total Base Year}\\ \text{CBD Employment}\end{array} \times \begin{array}{c}\text{\% of Workers}\\ \text{Present on}\\ \text{Average Day}\end{array} \times \begin{array}{c}\text{\% of Trips}\\ \text{on Freeways}\end{array} \times \begin{array}{c}\text{Study Freeway}\\ \text{ADT Near CBD}\end{array}}{\begin{array}{c}\text{Sum of ADTs for all}\\ \text{Freeways Entering CBD}\end{array}} = \begin{array}{c}\text{Base Year}\\ \text{Morning Peak Work Trips}\\ \text{Entering CBD on Study Freeway}\end{array} \qquad \text{(Eq. 3)}$$

HOV lane ridership patterns indicate that these lanes primarily serve trips to the CBD (8). Peak-hour HOV lane ridership estimates used in this study include only 25 percent additional trips for the areas outside the CBD served by transit and vanpools (Equation 4).

HOV lane operating experience indicates that ridership will increase at a higher rate than mixed-flow traffic due to: 1) mainlane congestion (volume increases restricted by capacity); and 2) attractiveness of HOV service (as congestion increases, so does time savings). This report assumes that HOV ridership would increase 3.5 percent per year for 20 years, or 1 percent more per year than mainlane traffic. Equation 4 illustrates the assumptions used to obtain design year peak-hour ridership values from base year CBD work trips for each study freeway. Ultimately the ridership estimate may be an input variable into the B/C ratio estimation equation and users of this technique will be able to utilize more site specific values. HOV trip estimation procedures from local transit, planning and highway agencies would, thus, be important input values for HOV lane cost effectiveness studies. Table 6 summarizes ridership on existing priority lane projects. The ridership data illustrated by these projects (which include barrier

Table 6. Peak-Hour Utilization of Operating HOV Lane Projects



HOV Lane Facility	Peak-Hour HOV Lane Passengers (1000's)	Eligible HOV Lane Vehicles
EXCLUSIVE IN SEPARATE R.O.W.*		
1. Ottawa, Canada		
Southeast Transitway		Buses
Central Area Transitway		Buses
West Transitway		Buses
Southwest Transitway		Buses
2. Pittsburgh, PA		
East PatWay		Buses
South PatWay		Buses
FACILITIES IN FREEWAY R.O.W.**		
Exclusive Facilities		
1. Houston, Texas		
I-10 (Katy)		Buses, 3+
I-45 (North)		Buses, Vans
2. Los Angeles, I-10 (El Monte)		Buses, 3+
3. Washington, D.C.		
I-395 (Shirley)	(2 HOV Lanes)	Buses, 4+
I-66	(2 HOV Lanes)	Buses, 3+
Concurrent Flow		
1. Honolulu, Moanalua Fwy.		Buses, 2+
2. Los Angeles, Rte. 91		Buses, 2+
3. Miami, I-95		Buses, 2+
4. Orange County, Rte..55		Buses, 2+
5. Orlando, I-4		Buses, 2+
6. San Francisco, CA		
Bay Bridge	(3 HOV Lanes)	Buses, 3+
US 101		Buses, 3+
7. Seattle, WA		
I-5		Buses, 3+
SR 520		Buses, 3+
Contraflow		
1. Honolulu, Kalanianaole Fwy.		Buses, 4+
2. New York City, I-495		Buses
3. San Francisco, CA US 101		Buses

*These facilities are 2-lane, 2-direction and the volumes are 2-direction volumes

**Peak-direction volumes

Source: Institute of Transportation Engineers 1985 Survey of Operating HOV Lane Projects separated HOV lanes as well as concurrent and contraflow lanes) defines the range of current ridership data for successful projects.

$$\begin{array}{c} \text{Base Year} \\ \text{Morning Peak} \\ \text{CBD Work Trips} \end{array} \times \begin{array}{c} \text{45\%} \\ \text{Mode Share} \end{array} \times \begin{array}{c} \text{50\% Ridership} \\ \text{in Peak-Hour} \end{array} \times \begin{array}{c} \text{1.25 (25\% Ridership to} \\ \text{Areas Outside CBD)} \end{array}$$

$$\times \begin{array}{c} \text{3.5\% Per Year} \\ \text{Ridership Growth} \\ \text{for 20 Years} \end{array} = \begin{array}{c} \text{Design Year} \\ \text{Peak-Hour HOV Lane} \\ \text{Ridership} \end{array} \qquad \text{(Eq. 4)}$$

Base Year Radial Freeway Characteristics

Utilizing data collected for the FREQ7 simulation model, several specific base year values were estimated for comparison with B/C ratios derived for each HOV lane project. Average freeway speed, congestion patterns, CBD work trips and freeway mainlane volume (Table 7) are factors which are both easily estimated and illustrative of freeway operating condition. These are the two most important facets of an analysis technique that attempts to provide relatively accurate, easily determined B/C ratios.

Table 7. Original Freeway Model HOV Lane B/C Ratio Indicators

Freeway Model	Base Year Peak-Hour Speed (mph)	Base Year Queueing Analysis[1] Time (hours)	Time (lane-hours)	Distance (miles)	Distance (lane-miles)	Base Year Daily CBD Work Trips	Design Year Peak-Hour HOV Lane Ridership	Base Year Average Daily Traffic Per Lane
A	37	2.25	6.75	5.4	16.9	22,000	12,300	20,000
B	37	2.50	7.50	6.3	18.9	19,000	10,650	19,900
C	25	2.75	8.25	8.3	24.9	18,400	10,300	19,500
D	25	3.25	6.50	9.1	19.4	13,100	7,350	19,200
E	38	1.75	7.00	2.9	11.5	12,200	6,850	14,900
F	25	2.00	4.00	9.3	18.6	5,700	3,100	21,900
G	40	1.50	3.50	3.1	7.2	12,500	7,000	25,600
H	29	2.25	6.75	6.3	18.9	15,500	8,700	16,000
I	43	0.75	2.25	1.4	4.2	5,200	2,900	16,500
J	38	1.25	3.50	2.3	6.7	7,000	3,900	12,200

[1] Time and distance of freeway operations below 35 mph.

Peak-Hour Mainlane Freeway Speed

The peak-hour, peak-direction freeway mainlane average speed from the FREQ7 simulation model is an indicator of the freeway operating condition. This average speed is calculated for the entire length of the section of freeway studied.

Freeway Mainlane Congestion Information

The queueing pattern data collected from travel time runs illustrates the extent, in both distance and time, of depressed level-of-service operation. This is presented in hours and miles, as well as freeway lane-hours and freeway lane-miles.

Central Business District (CBD) Work Trips

The combination of CBD employment and average daily traffic (ADT) are utilized (Equation 3) to obtain an estimate of the morning peak trips to the CBD. This estimate of the number of people destined for the CBD is a measure of the magnitude of potential HOV lane ridership.

Design Year Peak-Hour HOV Lane Passenger Volume

This factor is the number of person trips estimated to transfer from the mixed-flow freeway lanes to the HOV lane. CBD work trip values and mode share information are combined (Equation 4) to determine this value for use in the FREQ7 analysis.

Freeway Mainlane Average Daily Traffic Per Lane (ADT/Lane)

An estimate of base year ADT per lane for the entire freeway length modeled is used as an easily obtained quantification of average freeway mainlane operating condition.

Expansion of the FREQ7 Freeway Model Data Base

The ten radial freeway simulation models listed in Table 7 represent a better data base than the three circumferential freeway models. The radial data base is further enhanced, however, by the addition of models based on the original ten simulations. Utilizing the growth rate capability of the SYNPD2 model package, the input values for entrance and exit ramp volumes were decreased by 10 percent to form another 10 models for use in the HOV lane B/C ratio analysis. Decreasing the volumes by only 10 percent had two advantages: 1) mainlane operating condition for the existing models already covered the congested end of the indicators; and 2) freeway operations changed enough to simulate different base year conditions without altering the operation of the model by a large amount.

This process required an adjustment in the labeling sequence (e.g., Freeway A original model (AO) and Freeway A ten percent decrease model (AT)). The reduction in mainlane volume, in most cases, significantly alters freeway operations. The values in Table 8 for peak-hour speed and queueing are derived from FREQ7 output. The CBD work trip, design year peak-hour HOV lane ridership and average daily traffic per lane values were estimated by subtracting 10 percent from the original model values.

Table 8. Expanded Data Set of HOV Lane B/C Ratio Indicators

Freeway Model	Base Year Peak-Hour Speed (mph)	Base Year Queueing Analysis[1]				Base Year Daily CBD Work Trips	Design Year Peak-Hour HOV Lane Ridership	Base Year Average Daily Traffic Per Lane
		Time		Distance				
		(hours)	(lane-hours)	(miles)	(lane-miles)			
AO	37	2.25	6.75	5.4	16.9	22,000	12,300	20,000
AT	55	0	0	0	0	20,000	11,200	18,000
BO	37	2.50	7.50	6.3	18.9	19,000	10,650	19,900
BT	48	1.00	3.00	3.4	10.2	17,100	9,550	17,900
CO	25	2.75	8.25	8.3	24.9	18,400	10,300	19,500
CT	53	0	0	0	0	16,600	9,300	17,600
DO	25	3.25	6.50	9.1	19.4	13,100	7,350	19,200
DT	47	0.75	1.50	2.0	4.0	11,800	6,600	17,300
EO	38	1.75	7.00	2.9	11.5	12,200	6,850	14,900
ET	54	0	0	0	0	11,000	6,150	13,400
FO	25	2.00	4.00	9.3	18.6	5,700	3,100	21,900
FT	47	0.50	1.00	1.7	3.4	5,100	2,850	19,700
GO	40	1.50	3.50	3.1	7.2	12,500	7,000	25,600
GT	51	0	0	0	0	11,250	6,300	23,000
HO	29	2.25	6.75	6.3	18.9	15,500	8,700	16,000
HT	40	0.75	2.25	3.2	9.6	13,950	7,800	14,400
IO	43	0.75	2.25	1.4	4.2	5,200	2,900	16,500
IT	51	0	0	0	0	4,700	2,650	14,900
JO	38	1.25	3.50	2.3	6.7	7,000	3,900	12,200
JT	53	0.50	1.25	0.8	2.0	6,300	3,550	11,000

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[1] Time and distance of freeway operations below 35 mph.

HOV LANE COST EFFECTIVENESS INDICATORS

Adjustments Required For FREQ7 Models

In advance of any analysis of the potential for prediction of B/C ratios, some FREQ7 simulation model adjustments should be summarized. The use of constant factors for growth, mode share, and cost of HOV lane construction and maintenance facilitated comparison of the estimated B/C ratios. Unfortunately, some adjustments of individual models are required in the modeling and B/C ratio calculation process. For example, equalizing the passenger-miles of travel for the design year freeway and freeway/HOV lane models (Equation 1) is a "model-specific" operation that varies in magnitude.

Two Peak-Direction Freeway Lane Models

Another problem with the design year FREQ7 model operation relates to the effect of traffic volume growth on those freeways with only two peak-direction lanes over a significant length. Freeways D, F and G (Table 4), when subjected to a 2.5 percent per year traffic growth rate, become congested for almost all of the six-hour modeling period. The congestion resulted in a large number of passenger-miles not being counted by FREQ7 for both the "freeway-only" and freeway/HOV lane combination. Mainlane speeds showed small or no improvement due to HOV lane implementation (unlike the other models) despite significant peak-hour HOV lane passenger volumes (between 3,000 and 7,500).

The impact of the two-lane freeway configuration was investigated by adding one lane to the design year freeway mainlane model in both scenarios. Estimated HOV lane B/C ratios for G and D decreased, while those for the two Freeway F models (FO and FT) increased. The G and D reactions are intuitive; if more lanes are available for mixed-flow traffic, average speeds will increase and the benefit derived from HOV lane usage will decrease. The counter-intuitive increase in both FO and FT model B/C ratios is the result of the extremely congested operation of the two-lane models. The average freeway speed for the three-lane freeway is higher than that for the two-lane configuration. An HOV lane with the three-lane system provides benefits to priority vehicles just as with the two-lane freeway. The HOV lane also increases travel speed on the three mainlanes (relative to the "freeway-only" model) by removing persons from mixed-flow vehicles. This component of the benefit estimation is not present for the two-lane freeway; freeway operations do not improve with an HOV lane. The increase in FO and FT HOV lane B/C ratios (from 2.5 and 1.6 to 3.8 and 2.1, respectively) could, thus, be assigned to problems with HOV lane analyses using the FREQ7 model. The high growth rate and constrained capacity results in an artificially low B/C ratio for Freeway F. The higher B/C ratios are, thus, used in the analysis while the original (higher) HOV lane B/C ratios for Freeways G and D are retained.

In actual practice this situation should not occur frequently. The peak-period, peak-direction nature of the HOV lane improvement can provide significant benefit to motorists, but four-lane freeways with base year ADT per lane values in excess of 20,000 (and design year volumes above 32,000 per lane) warrant an improvement that provides significant two-direction capacity increases across the entire day. Analyses of mixed-flow capacity increases and HOV lane construction, to be implemented concurrently, would be appropriate.

Additional Low B/C Ratio HOV Lane Models

The other initial adjustment to the set of twenty models addresses one of the primary goals of this study. If the B/C ratio estimation model is to be used to determine the appropriate time for a detailed analysis effort, a clear definition of FREQ7 model behavior on the low end of the B/C ratio scale (e.g., B/C less than 2.0) is required. The FREQ7 models used in this study were originally developed because severe traffic congestion was occurring or forecast on several Texas urban freeways -- a problem that could be decreased by HOV lane implementation. The higher HOV lane B/C ratios are, thus, over represented, and the lower B/C ratios, those important to the definition of the relationship between freeway operating condition and the need for a detailed analysis of HOV lane feasibility, are under represented.

Model J had a relatively low B/C ratio and Models D, F and G (the other relatively low HOV lane B/C ratios) had long sections of two-lane freeway, which somewhat limits their usefulness. Models H and I had medium to low B/C ratios and could be easily modified to provide additional data points. The significant operating condition improvements required to lower the B/C ratio were accomplished by utilizing the base year as the new design year and creating a new base year 20 years in the past (using the 2.5 percent per year growth). These new models carry a "-20" label, along with new base year freeway operating parameters.

B/C Ratio Versus Independent Variables

The B/C ratio calculation was applied to the expanded list of twenty-four FREQ7 simulation models. The B/C ratios are presented in Table 9 along with the eight possible cost effectiveness indicators from Table 8. Graphical representations of the eight individual relationships are shown in Figures 3 through 10. The coefficient of determination (R^2), which measures the strength of the relationship between the dependent variable (B/C ratio) and independent variable(s) (the eight indicators), is presented for each relationship in Table 10. The "x=1.0" R^2 values represent the "best fit" that could be obtained using a relatively simple linear relationship. Other, more complex functional forms of the models could possibly provide better fits. Table 10 also summarizes R^2 values for two other linear relationships (B/C versus indicator raised to some power) and multivariable relationships (B/C versus more than one indicator).

The ultimate model would obviously not be as useful with eight factors if two or three were sufficient to provide a good correlation between B/C ratio and freeway condition. In addition, it must be recognized that not all of these factors are totally independent of each other. The peak-hour HOV lane ridership is derived from the CBD work trips using the same set of factors for all freeways. It is not surprising that the R^2 values for these factors are similar. The same logic could be applied to the time (hours and lane-hours) and distance (miles and lane-miles) queueing measures. While these are less closely related than CBD work trips and ridership, it would probably be undesirable to have both time or both distance factors in a

Table 9. B/C Ratio and Freeway Operating Condition Indicators

Freeway Model	Peak-Hour Speed (mph)	Queueing Analysis				CBD Work Trips	Design Year Peak-Hour HOV Lane Ridership	Average Daily Traffic Per Lane	Benefit-Cost Ratio
		Time		Distance					
		(hours)	(lane-hours)	(miles)	(lane-miles)				
AO	37	2.25	6.75	5.4	16.9	22,000	12,300	20,000	10.0
AT	55	0	0	0	0	20,000	11,200	18,000	7.1
BO	37	2.50	7.50	6.3	18.9	19,000	10,650	19,900	6.8
BT	48	1.00	3.00	3.4	10.2	17,100	9,550	17,900	5.9
CO	25	2.75	8.25	8.3	24.9	18,400	10,300	19,500	7.1
CT	53	0	0	0	0	16,600	9,300	17,600	4.2
DO	25	3.25	6.50	9.1	19.4	13,100	7,350	19,200	2.9
DT	47	0.75	1.50	2.0	4.0	11,800	6,600	17,300	1.7
EO	38	1.75	7.00	2.9	11.5	12,200	6,850	14,900	5.0
ET	54	0	0	0	0	11,000	6,150	13,400	3.9
FO	25	2.00	4.00	9.3	18.6	5,700	3,100	21,900	3.8
FT	47	0.50	1.00	1.7	3.4	5,100	2,850	19,700	2.1
GO	40	1.50	3.50	3.1	7.2	12,500	7,000	25,600	4.3
GT	51	0	0	0	0	11,250	6,300	23,000	3.3
HO	29	2.25	6.75	6.3	18.9	15,500	8,700	16,000	4.3
HT	40	0.75	2.25	3.2	9.6	13,950	7,800	14,400	3.4
IO	43	0.75	2.25	1.4	4.2	5,200	2,900	16,500	1.8
IT	51	0	0	0	0	4,700	2,650	14,900	1.4
JO	38	1.25	3.50	2.3	6.7	7,000	3,900	12,200	1.1
JT	53	0.50	1.25	0.8	2.0	6,300	3,550	11,000	1.0
HO-20	51	0	0	0	0	7,400	5,300	9,800	0.7
HT-20	52	0	0	0	0	6,700	4,800	8,800	0.3
IO-20	56	0	0	0	0	9,500	4,200	9,100	0.5
IT-20	57	0	0	0	0	8,600	3,800	8,200	0.2

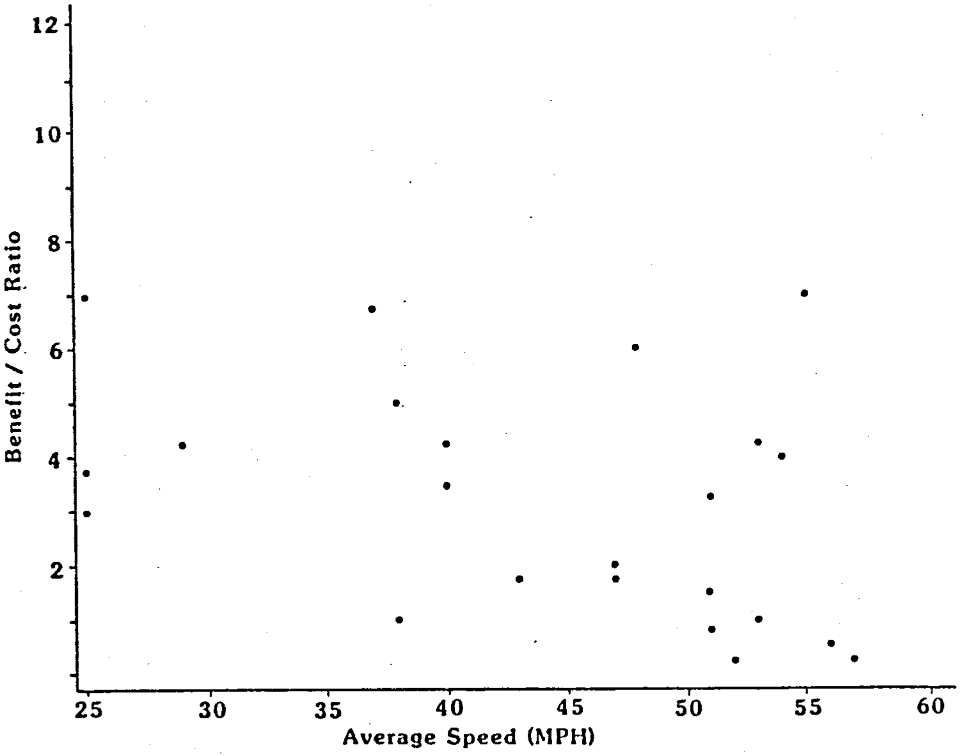

Figure 3. Data Points for Average Speed Versus HOV Lane Benefit/Cost Ratio

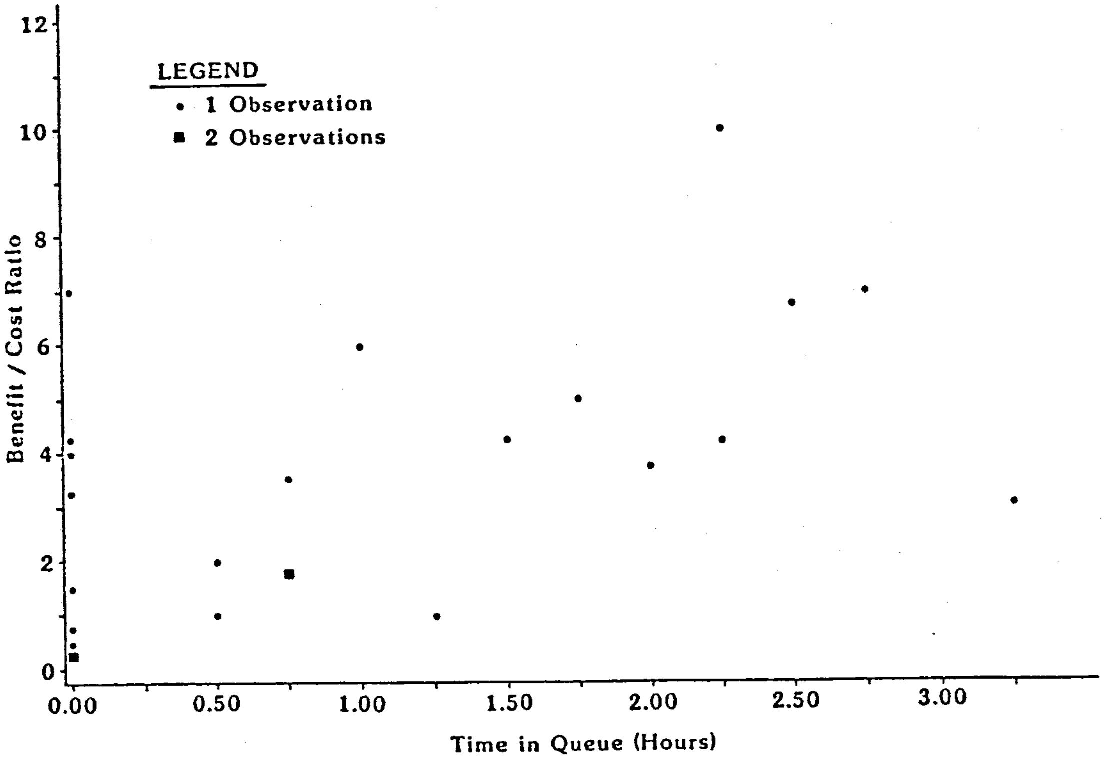

Figure 4. Data Points for Hours in Queue Versus HOV Lane Benefit/Cost Ratio

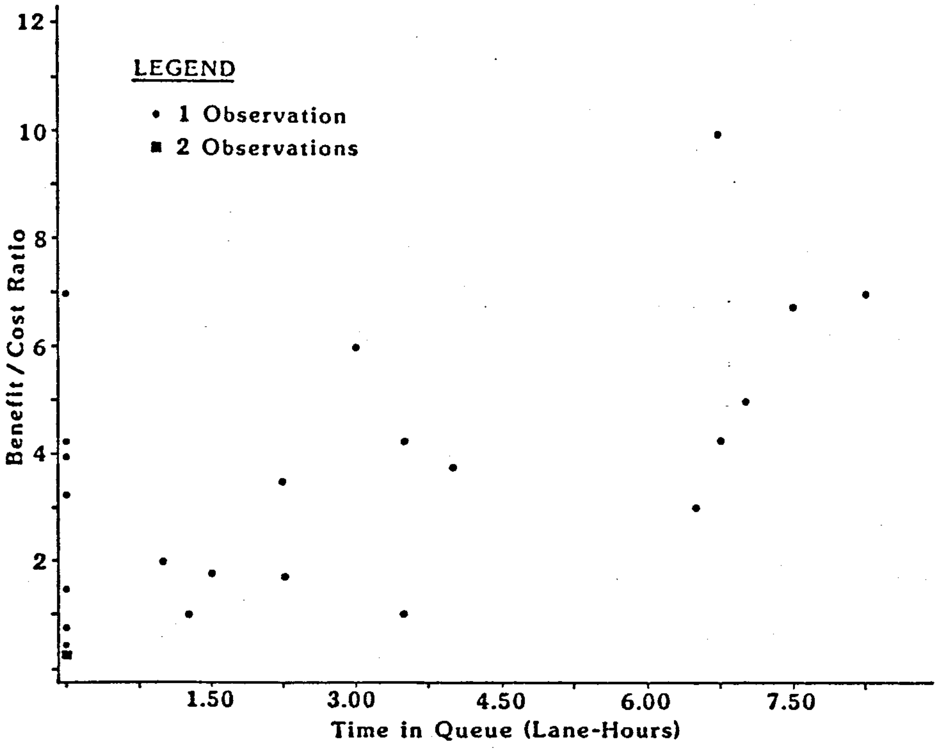

Figure 5. Data Points for Lane-Hours of Queue Versus HOV Lane Benefit/Cost Ratio

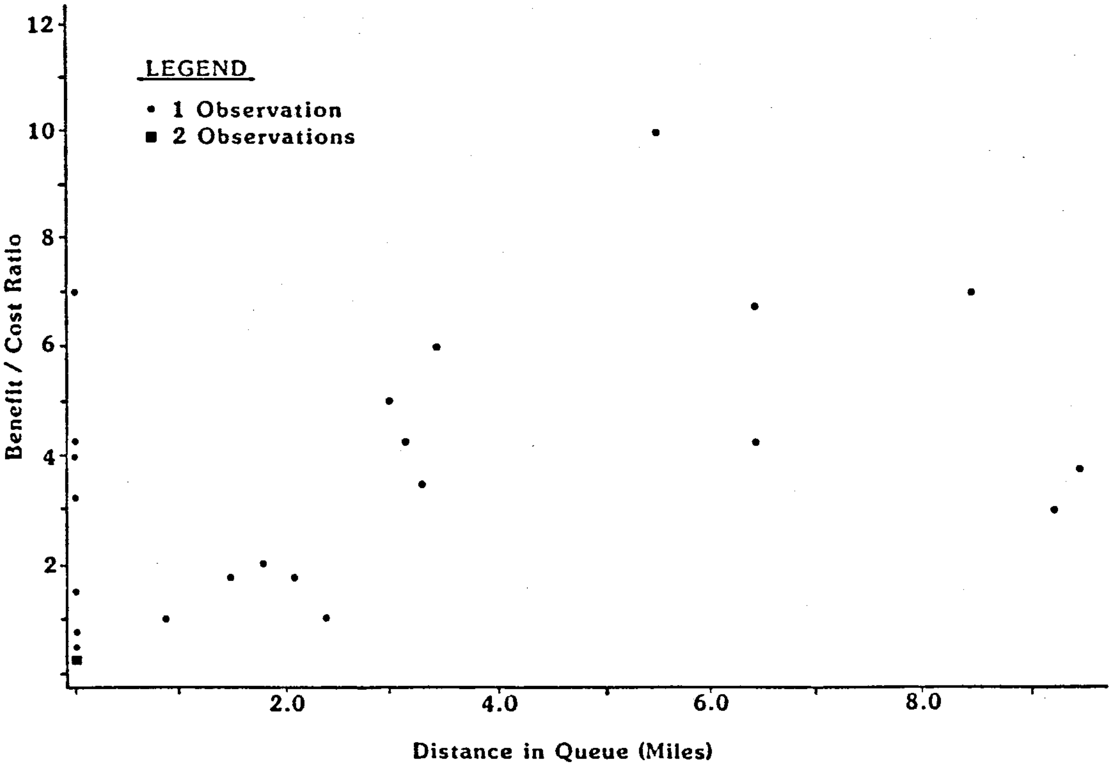

Figure 6. Data Points for Miles in Queue Versus HOV Lane Benefit/Cost Ratio

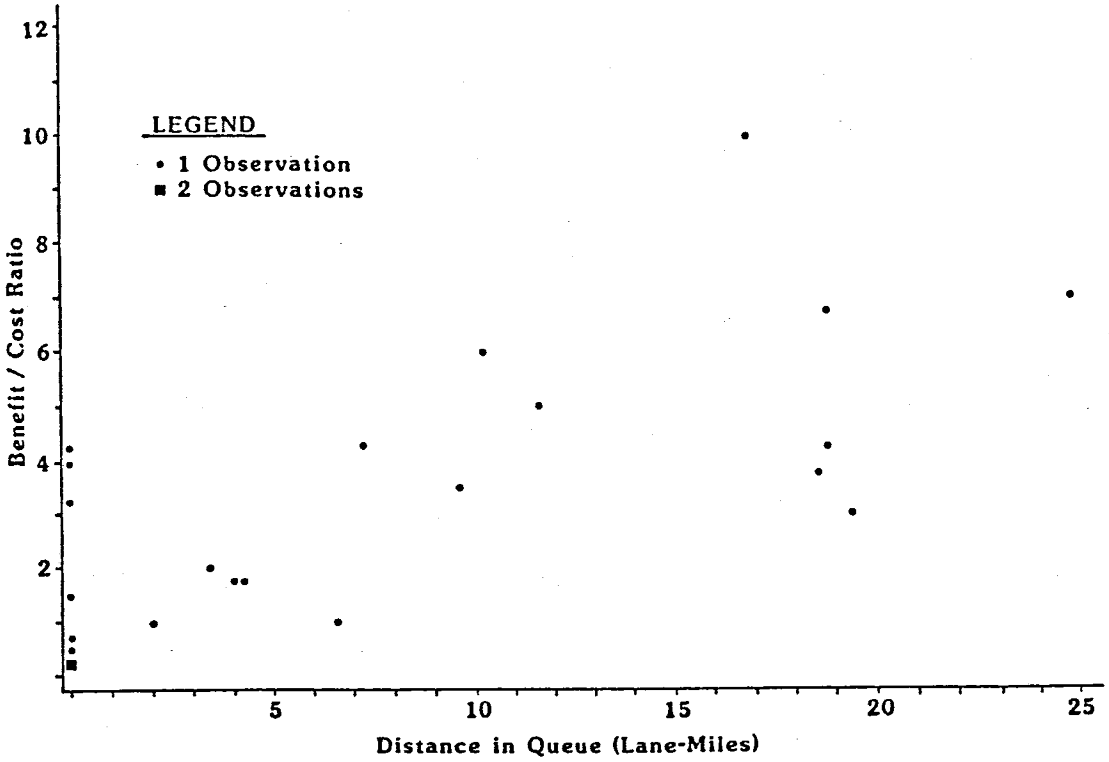

Figure 7. Data Points for Lane-Miles in Queue Versus HOV Lane Benefit/Cost Ratio

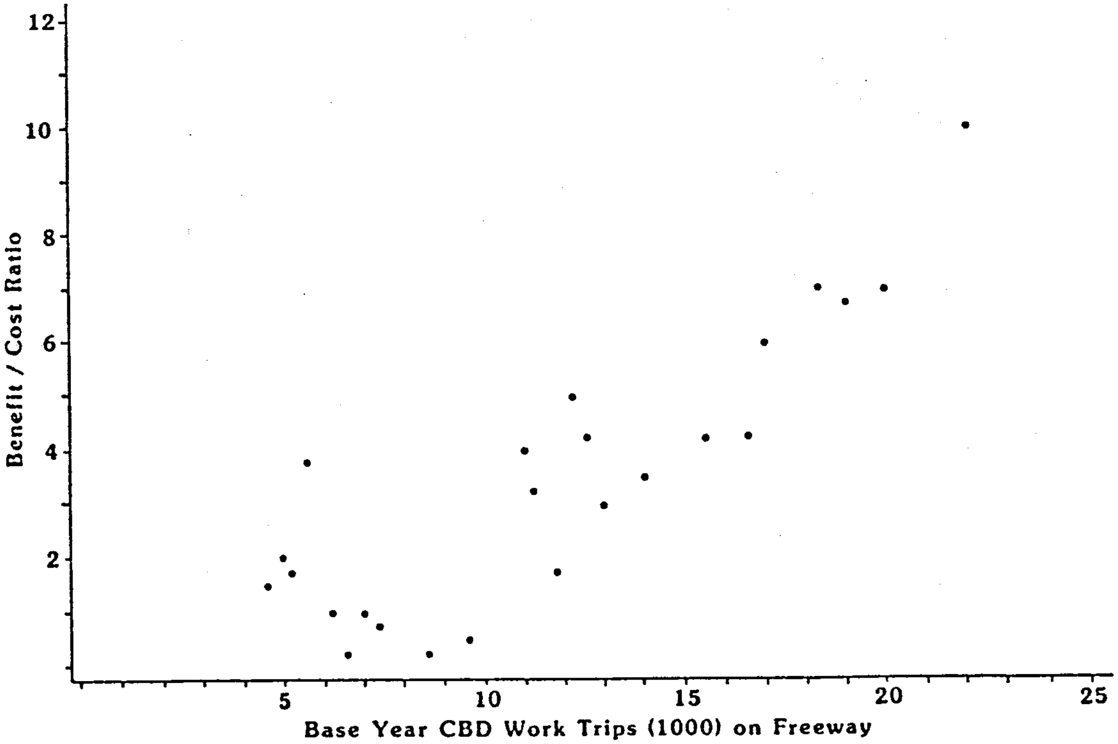

Figure 8. Data Points for CBD Work Trips Versus HOV Lane Benefit/Cost Ratio

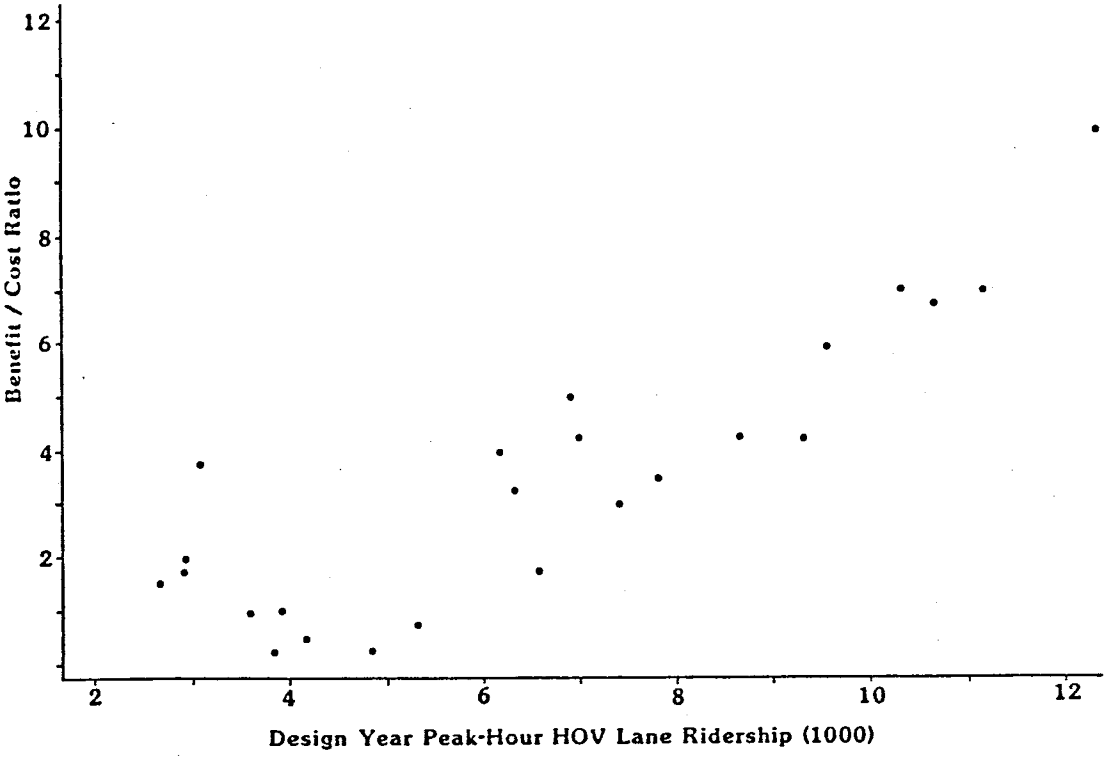

Figure 9. Data Points for Peak-Hour HOV Lane Ridership Versus HOV Lane Benefit/Cost Ratio

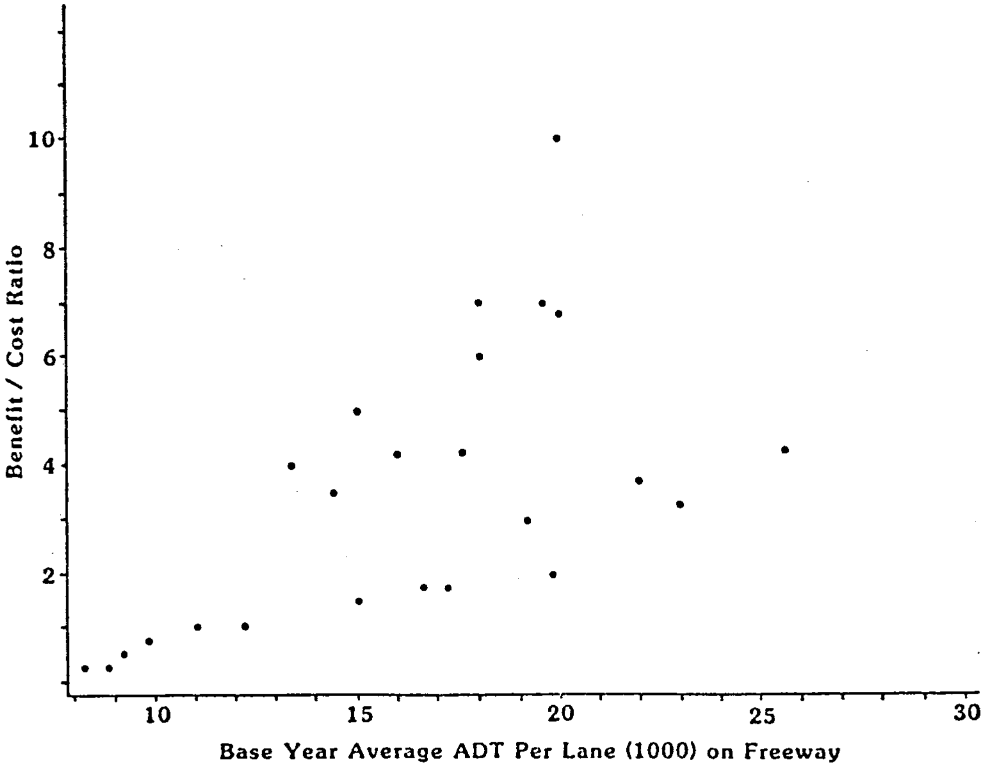

Figure 10. Data Points for Average ADT Per Lane Versus HOV Lane Benefit/Cost Ratio

Table 10. Coefficients of Determination (R^2) For Benefit-Cost Ratio Estimation Models (24 Freeway Models)

Independent Variables Included in Regression Model	R^2 Value For Model of B/C Ratio vs. Variable to X Power		
	X = 0.5[1]	X = 1.0	X = 2.0[2]
ADT Per Lane (APL)	0.40	0.38	0.32
Average Speed (AVGSP)	0.16	0.17	0.17
CBD Work Trips (WTRIP)	0.69	0.75	0.82
Peak-Hour Ridership (PHRID)	0.69	0.75	0.82
Hours of Queue (TIME)	0.24	0.29	0.24
Lane-Hours of Queue (LNHR)	0.28	0.37	0.40
Miles of Queue (DIST)	0.24	0.24	0.15
Lane-Miles of Queue (LNMI)	0.29	0.35	0.33
All Eight Variables	0.87	0.91	0.94
APL, WTRIP2, TIME, LNMI		0.90	
APL, WTRIP2, LNHR2, LNM12		0.90	
APL, WTRIP2, LNHR, LNMI		0.90	
APL, PHRID, LNHR, LNMI		0.85	
APL, WTRIP, TIME, DIST		0.84	
APL, PHRID, TIME, DIST		0.84	
APL, WTRIP, LNHR		0.85	
APL, WTRIP		0.83	
APL, WTRIP2		0.89	
APL, PHRID		0.83	
APL, PHRID2		0.89	
APL, PHRID5		0.79	
APL5, PHRID		0.84	
APL5, PHRID5		0.84	

[1] Square root of variable (e.g., PHRID5)

[2] Square of variable (e.g., PHRID2)

Note: R^2 values with different numbers of variables are not comparable but are presented for illustration purposes only.

model. The three regression models in Table 10 with all eight factors included might, thus, be an indication of the highest attainable coefficient of determination, rather than statistically viable model alternatives.

The CBD work trips and design year peak-hour HOV lane ridership factors have very high R^2 values when compared individually with B/C ratios. ADT per lane, lane-hours and lane-miles of queue are the next most effective predictors, although only approximately half that of the first two. Squaring or taking the square root of each variable produces a better correlation than the "x=1.0" relationship in four of the eight variables. In only two of these cases, CBD trips and HOV ridership, however, is there any substantial difference. The R^2 values for these two factors are very high for all relationships, and the ability to predict B/C ratios may not be greatly enhanced relative to a more cumbersome procedure.

The best multiple variable combinations are also presented in Table 10. R^2 values range between 0.79 and 0.90 for the models, all of which contain ADT per lane and either work trips or ridership. The models with three and four variables provide the best correlation, but, as a useful planning tool, they are relatively complicated. A model that includes the factors base year ADT per lane and design year peak-hour ridership would combine the key desirable features of easy data collection using generally available planning statistics, ease of use (only two factors), and good ability to predict benefit/cost ratios.

Additional Independent Variable Values

Before the final determination of the model components, however, the graphs in Figures 9 and 10 must be further expanded to include data points over the whole range of independent variable values. The adjustments (-20) to freeway models HO, HT, IO and IT resulted in very low B/C ratios. Those B/C ratios illustrate the relationship between low ADT per lane and low B/C ratio values. The relationship for low HOV lane ridership, however, was not as well defined. To remedy this, relatively low peak-hour ridership values (1,200, 1,700 and 2,200) were used in conjunction with freeway models BO, DO, IO and JO and medium ridership levels (4,000 and 5,000) were used with models

DO, EO and JO. These freeway models provided a range of base operating conditions and benefit/cost ratios. This procedure, however, did not correlate ridership with work trips as closely as the initial 24 models. Table 11 summarizes the additional B/C ratio and design year peak-hour ridership data points illustrated in Figure 11. The coefficient of determination for this new graph (with 41 data points) is 0.72.

Table 11. Additional Peak-Hour HOV Lane Ridership Values and Associated B/C Ratios

Freeway Model	Design Year Peak-Hour HOV Lane Ridership	Benefit/Cost Ratio
BO	1200	1.4
	1700	1.9
	2200	2.3
DO	1200	0.8
	1700	1.0
	2200	1.3
IO	1200	0.8
	1700	1.0
	2200	2.1
JO	1200	0.3
	1700	0.4
	2200	0.5
DO	4000	1.9
	5000	2.2
EO	4000	3.6
	5000	4.5
JO	5000[1]	1.4

[1] Original Model J was very close to 4000 ridership.

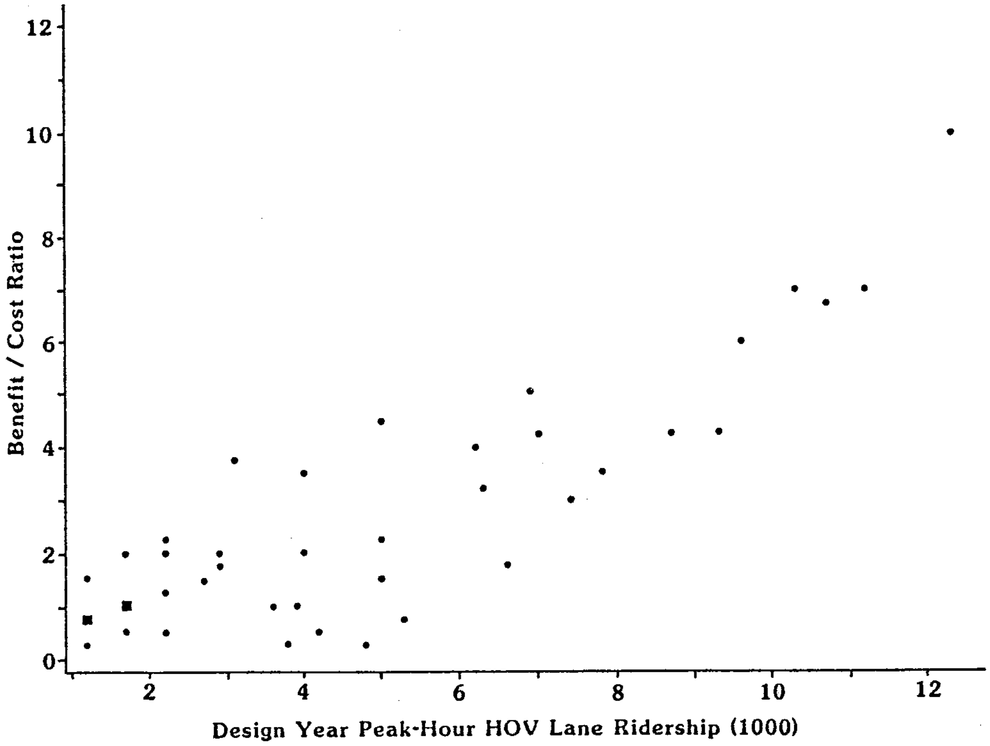

Figure 11. Expanded Data Set for Peak-Hour HOV Lane Ridership Versus HOV Lane Benefit/Cost Ratio

B/C Ratio Estimation Model

The most common and easily utilized multiple variable regression technique requires that each independent variable have the same number of observations. The additional peak-hour ridership values (Table 11) resulted in a disparity in the number of observations between that factor and ADT per lane. For the R^2 value calculation, the original base model ADT per lane numbers were matched with the new ridership and B/C ratio data. The new ridership values, however, were chosen arbitrarily based on the need to eliminate gaps in the graph, rather than being derived from a combination of

ADT and CBD employment. The relationship between B/C ratio and ADT per lane and ridership, however, remains very strong, with an R^2 value of 0.82 for the model with 41 data sets (compared to the R^2 of 0.83 for the 24 data set model).

Test For Multicollinearity

The derivation of peak-hour ridership utilized freeway ADT. If the two independent variables included in the model (base year ADT per lane and design year peak-hour HOV lane ridership) were closely related, the usefulness of the model to predict changes in B/C ratios based upon changes in one variable (with the other remaining constant) would be lessened. The effect, known as multicollinearity, occurs when one variable is basically a constant factor of another. Changing the numerical value of one independent variable and judging the effect on the dependent variable would not be a valid comparison, as the collinear relationship would require that both variables change.

A formal method of determining multicollinearity problems utilizes the variance inflation factor (VIF). The process, described in "Applied Linear Regression Models" (9), was performed on the 24 sets of relatively correlated data. If multicollinearity was a problem, it would show most clearly in this set rather than the more random set of 41 data entries. The key indicator, the maximum VIF value, was estimated at 1.2; a value in excess of 10 would indicate an undue influence by the multicollinearity phenomenon. While HOV lane ridership is related to ADT through the CBD work trip estimate, the number of freeway lanes and different downtown employment estimates produced enough variability to disassociate ridership and ADT per lane.

B/C Ratio Estimation Equation

Previous sections have detailed the selection of a two-factor model for the B/C ratio estimation procedure. The analysis initially utilized constant traffic growth rates, mode share of CBD-bound work trips, and HOV lane cost values. Base year ADT per freeway lane and design year peak-hour HOV lane ridership should be relatively easy to obtain through local planning or transit agencies. With a coefficient of determination (R^2) equal to 0.82 (maximum R^2 = 1.0), these two factors should accurately predict the benefit/cost ratio using Equation 5.

$$\text{B/C Ratio} = -\,3.00 + 0.18\begin{bmatrix}\text{Base Year}\\ \text{ADT per Lane}\\ \text{(1000s)}\end{bmatrix} + \;0.57\begin{bmatrix}\text{Design Year}\\ \text{Peak-Hour HOV Lane}\\ \text{Ridership (1000s)}\end{bmatrix} \quad \text{(Eq. 5)}$$

where:

Annual mixed-flow traffic growth rate = 2.5 percent,
Annual HOV lane ridership growth rate = 3.5 percent,
HOV lane construction cost = $5 million per mile,
HOV lane operation and maintenance cost = $250,000 per year.

Table 12 summarizes the statistical test data for Equation 5. The t-test values indicate the significance of the individual parameter estimates. The p-values (less than 0.0001) represent the probability that each parameter is equal to zero. These very low p-values, when combined with the low p-value for the same type of test applied to the entire model (F-test), reinforce the high R^2 value. The two factors in Equation 5 explain 82 percent of the variability in the B/C ratio (R^2=0.82) and are both statistically significant (p-values are less than 0.0001).

Table 12. Level of Significance of Benefit/Cost Estimation Technique

Independent Variable	Parameter Estimate	Standard Error	t-Value for Parameter = 0	Level of Significance (p-value)
Average ADT per Lane	0.18	0.04	4.42	0.0001
Peak-Hour HOV Lane Ridership	0.57	0.05	11.13	0.0001

Note: Model F value = 84.12 and probability value (F-test) = 0.0001.

Equation 5, when calculated with relatively low ADT per lane and ridership values, could yield a negative B/C ratio. This estimate is probably incorrect (the actual result would be a very low positive value), but is derived from the negative y-intercept value. This minor inconsistency should not decrease the usefulness of the equation.

The variable coefficients (Equation 5 and Table 12) illustrate the sensitivity of the B/C ratio estimation procedure to traffic volume and ridership estimates. A change in HOV lane ridership of 1000 peak-hour passengers changes the B/C ratio by 0.57. This is approximately 3 times the B/C ratio change for a similar change in average ADT per lane. The ratio of coefficients and the high R^2 value for design year HOV lane ridership illustrate the importance of obtaining a relatively accurate estimate of this measure.

The more practical concern of deciding to build or not to build an HOV lane is depicted graphically in Figures 12 and 13. The best-fit (mean) line and the 95 percent confidence area were plotted for each measure. The horizontal lines at the 2.0 and 3.0 B/C ratio level delineate marginal projects. A B/C ratio lower than 2.0 would appear to make the project unwarranted, while a B/C ratio higher than 3.0 should take the project out of the marginal category and into a warranted situation.

Figure 12 illustrates the following demand-based guidelines that may be used to assess HOV lane cost effectiveness. The design year peak-hour ridership in all eligible vehicles on the HOV lane is highly correlated (R^2 = 0.75, Table 10) with the potential project B/C ratio. The constant growth and cost numbers previously used are reflected in these guidelines; additional information is presented later for varying growth and cost estimates.

- Less than 3000 design year peak-hour riders; HOV lane apparently not warranted;
- 3000 to 6000 peak-hour riders; HOV lane marginally warranted; and
- Over 6000 peak-hour riders; HOV lane apparently warranted.

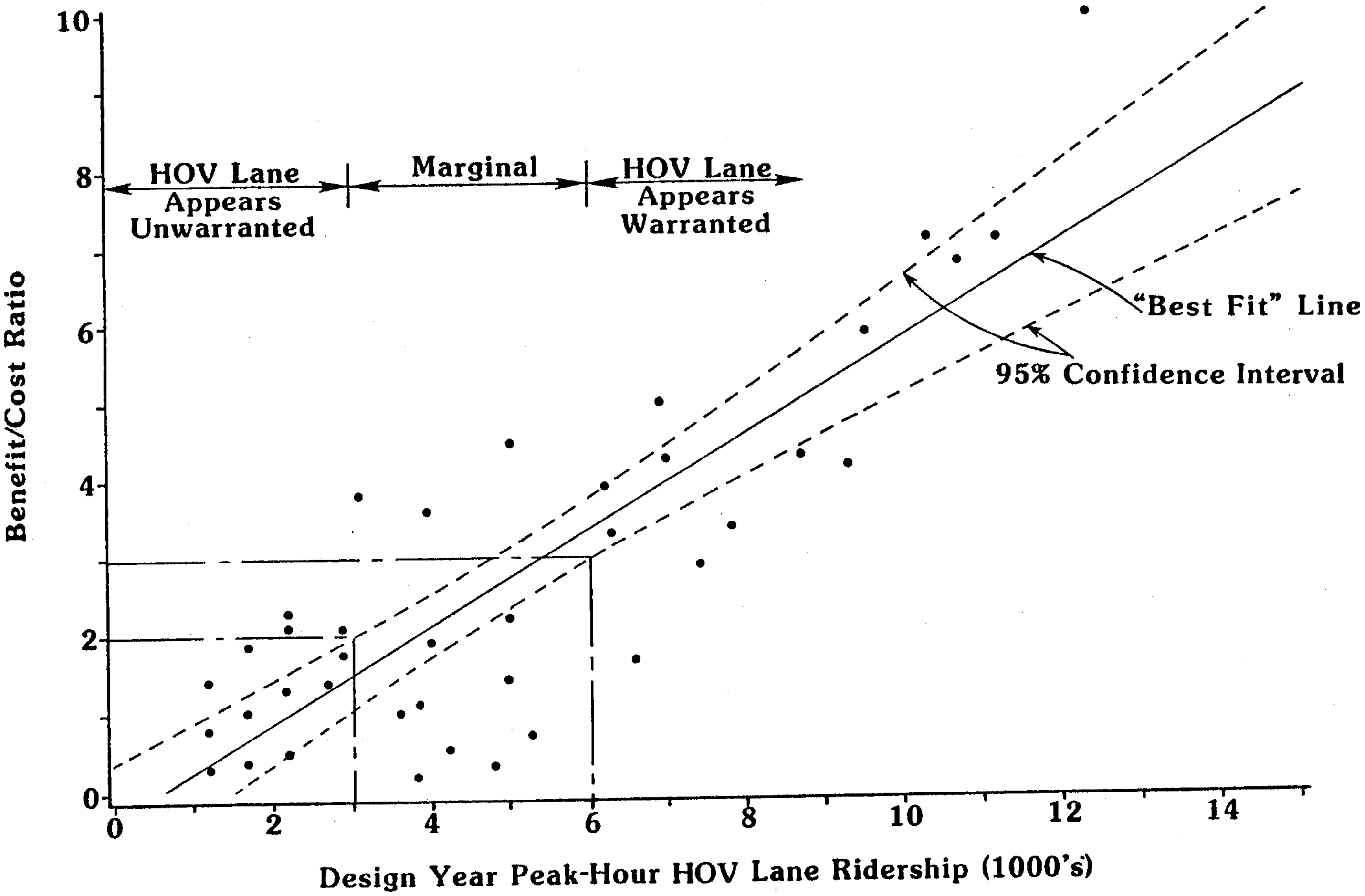

Figure 12. Relationship Between Design Year Peak-Hour HOV Lane Ridership and the Benefit/Cost Ratio of an HOV Lane Improvement

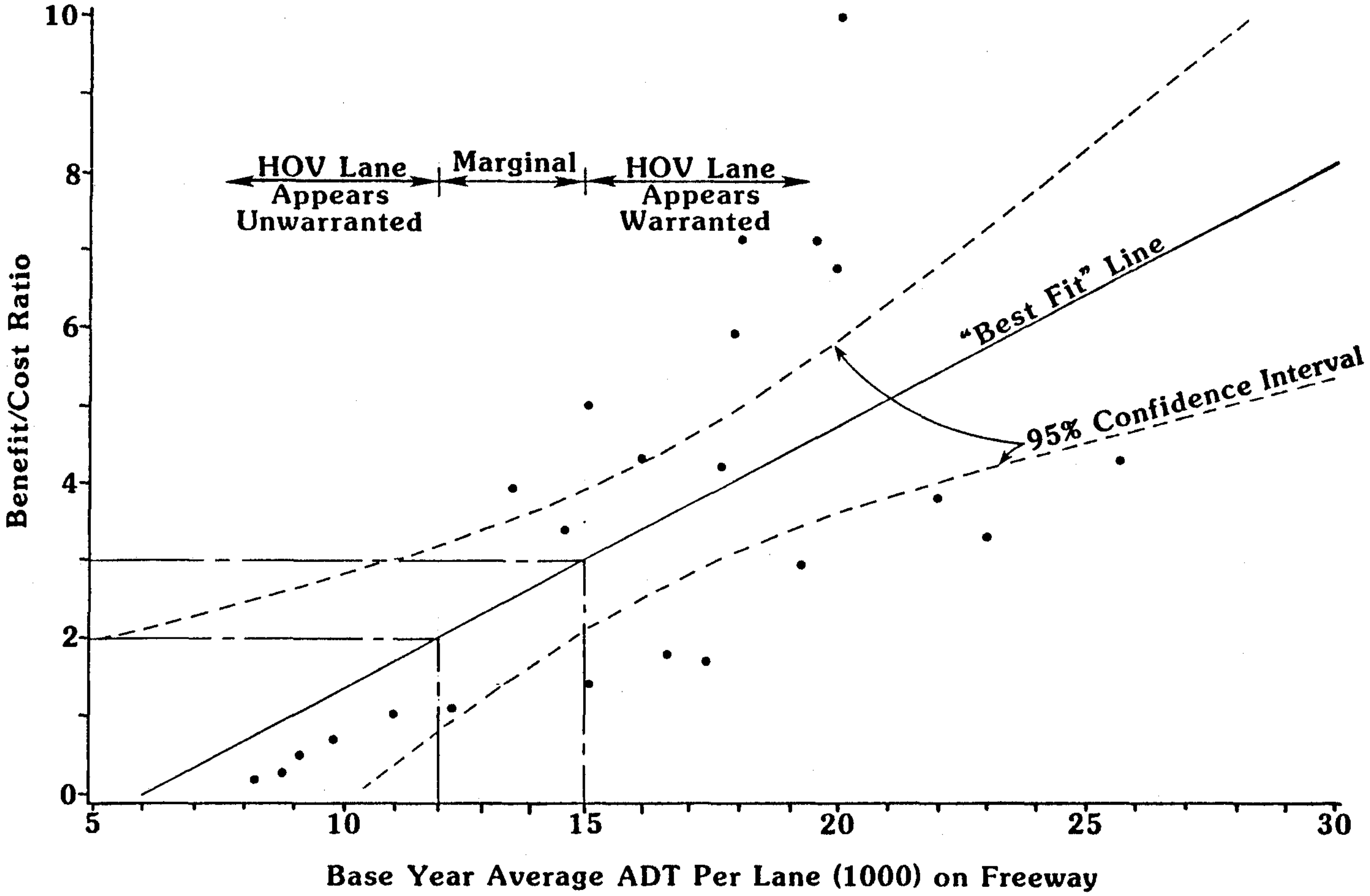

Figure 13. Relationship Between Base Year Average Freeway ADT Per Lane and the Benefit/Cost Ratio of an HOV Lane Improvement

The relatively small 95 percent confidence area reflects the high correlation between HOV ridership and B/C ratio. The range for marginally warranted projects extends across the 95 percent confidence area to include those areas that might warrant further investigation.

Figure 13 illustrates the following supply-related guidelines that may be used to assess HOV lane cost effectiveness. Traffic data for the initial year of HOV lane operation estimates the degree of freeway congestion, although with a much lower coefficient of determination ($R^2 = 0.38$, Table 10).

- Less than 12,000 base year ADT per lane; HOV lane apparently not warranted;
- 12,000 to 15,000 ADT per lane; HOV lane marginally warranted; and
- More than 15,000 ADT per lane; HOV lane apparently warranted.

The R^2 value is not as high for this measure as it is for ridership. The 95 percent confidence area is relatively large and, therefore, the average line is used to delineate the marginal project area. The 12,000 ADT per lane value should not, under normal peaking characteristics, result in significant mainlane congestion. The general rule of thumb for HOV lane effectiveness (savings of 1 minute per mile of HOV lane) would probably not be realized. The 2.5 percent per year traffic growth rate, when applied to the 12,000 vehicles per day per lane value, results in approximately 20,000 ADT per lane in the design year. Significant peak-hour congestion should be produced at this traffic level.

When combined, these two sets of guidelines suggest that, at relatively moderate ridership and urban freeway traffic levels, an HOV lane could be cost effective. An average of 12,000 vehicles per day per freeway lane would not indicate a severe peak-period congestion problem. Likewise, 3,000 peak-hour HOV lane riders is approximately the equivalent of one and one-half mixed-flow freeway lanes. This design year value could also be expressed as 1500 peak-hour riders in the base year (using the assumed 3.5 percent per year growth), less than one mixed-flow lane. Data for freeway corridors that approximate these levels of capacity supply and HOV facility demand would warrant the inclusion of HOV lanes in an alternative improvement analysis process.

Application of Study Data to Other Growth and Cost Values

The B/C ratio estimation model development process has utilized one growth rate and one cost estimate for each HOV lane project. This section summarizes the changes that are required to accept a greater range of values for these two key factors.

Cost Estimate Variation

Typical construction costs for the Houston HOV lane system were utilized in the initial analysis. The $5 million per mile cost includes all major items required to build a reversible, barrier-separated HOV lane in a freeway median and associated street and park-and-ride lot improvements. It does not, however, include the cost of buses and maintenance facilities required to operate transit on the lane. Yearly operating costs were estimated at $250,000 based on the Houston experience; the present value of the 20-year operating cost (using the 10 percent discount rate) is approximately $2.2 million.

If values significantly different from these are expected, Equation 5 and the graphs in Figures 12 and 13 can be altered (Equation 6). The new average cost per mile is combined with the $5 million per mile cost to estimate a new B/C ratio.

$$\begin{array}{c}\text{B/C Ratio}\\ \text{for New}\\ \text{Capital Cost}\end{array} = \frac{\begin{array}{c}\text{\$5 Million}\\ \text{per Mile of}\\ \text{HOV Lane}\end{array}}{\begin{array}{c}\text{New HOV Lane}\\ \text{Cost per Mile}\end{array}} \times \begin{array}{l}\text{B/C Ratio From}\\ \text{Eq. 5 and}\\ \text{Figures 12 and 13}\end{array} \qquad \text{(Eq. 6)}$$

Traffic Growth Rate Variation

Use of a consistent growth rate for all models in the analysis allowed a better determination of the effect of several other factors. Actual planning decisions, however, usually require a variety of growth rates within one corridor. This benefit/cost estimation technique does not easily allow multiple growth rates in one corridor, but the following information provides some guidance as to expected B/C ratios under a variety of projected growth conditions.

Annual traffic growth rates between 1.0 and 4.0 percent were used with eight different HOV lane models to develop Table 13. The area of significant analysis is the marginal and not cost effective HOV lane facilities. Projects that are clearly cost effective (e.g., Freeway B) have a lower B/C ratio with a slower growth in traffic and mainlane congestion. Those facilities, however, remain cost effective at low growth rates due to high base year congestion levels and would warrant a more intensive feasibility investigation at almost any traffic growth rate.

The conclusions on HOV lane projects for less congested freeways may change significantly depending on the projected traffic growth rate. Compared to the 2.5 percent per year growth rate assumed in the main section of this study, a 30 percent change in growth is estimated to change the B/C ratio 20 to 25 percent. A decrease or increase of 60 percent from the basic 2.5 percent per year growth rate results in a 45 to 60 percent change in B/C ratio.

Models 4 and 5 illustrate the importance of considering alternative growth rates during the initial HOV lane planning process. The 2.5 percent annual growth rate, with the corresponding 3.5 percent HOV ridership growth rate, when applied to the two models resulted in unwarranted HOV lanes. The 4.0 percent annual growth rate, however, produces the estimate that an HOV lane is warranted.

Table 13. Benefit/Cost Ratios for Several Annual Growth Rates

Model Number	Freeway Model	Annual Mixed-Flow Traffic Growth Rate for 20-Year Period (Percent)[1]				
		1.00	1.75	2.50[2]	3.25	4.00
1	BO	5.2	6.6	6.8	---[3]	---[3]
2	BT	4.3	5.0	5.9	---[3]	---[3]
3	DO	1.8	1.9	2.9	3.3	4.2
4	IO	0.9	1.3	1.8	2.4	3.3
5	DT	0.6	1.2	1.7	2.2	3.0
6	IT	0.5	1.0	1.4	1.8	2.5
7	JO	0.8	1.1	1.1	1.4	2.0
8	JT	0.6	1.0	1.0	1.0	1.4
Average of B/C Ratio for Models 3 to 8		0.9	1.3	1.7	2.0	2.7
Change From B/C Ratio with 2.5 Percent Annual Growth		-45%	-25%	----	+20%	+60%

[1] Annual average HOV lane traffic growth rate is 1.0 percent higher than mixed-flow.

[2] Growth rate assumed for original analysis.

[3] HOV lane model not tested; B/C ratio clearly warrants HOV lane.

CONCLUSIONS

As HOV lane projects have been considered for Texas freeways, extensive planning-level work has been required to assess the cost effectiveness of those projects. TTI has performed HOV feasibility analyses on several freeways in Houston, Dallas and San Antonio utilizing the FREQ7 computer freeway simulation model. The data collection and reduction effort required to calibrate these models is extensive. It appears that a need exists for criteria that can be used at the conceptual planning level to quickly and easily assess HOV lane feasibility. This report analyzes data for radial Texas freeways to determine the freeway operating conditions that need to exist to warrant more intensive study of HOV lane feasibility.

Figures 11 and 12 and Equation 5 illustrate the major findings of this report. Equation 5 requires the estimation of four input variables -- base year average freeway ADT per lane, design year peak-hour HOV lane ridership, traffic volume growth rate and HOV lane cost. The first and third may be obtained from generally available traffic data. The second and fourth can be developed during the initial planning process using trip pattern information and data derived from experiences with operational HOV lanes. Figures 11 and 12 delineate the conditions needed to warrant further HOV lane analysis based on selected values for traffic growth rate and HOV lane cost. Projects that do not appear cost effective may be deleted from the list of possible improvements warranting immediate study. Table 14 summarizes the findings of this report relative to estimated HOV lane cost effectiveness.

Table 10 presents the coefficients of determination (R^2) for several relationships between benefit/cost ratio, freeway operating condition and HOV lane demand. The combination of ADT per lane and HOV lane ridership as independent variables results in an R^2 value of 0.82 for the HOV lane B/C ratio estimation procedure. While slightly higher R^2 values are possible utilizing curvilinear relationships, the high correlation and relative simplicity of use made the linear equation appear more applicable. Another section of this report expanded the data base to include a variety of alternative traffic volume growth rates and HOV lane cost values. The high

R^2 for HOV lane ridership (Table 10) and the data in Table 13 concerning traffic growth rates detail the sensitivity of the B/C ratio to these measures. Relatively accurate planning data for these measures is, thus, desirable even at a fairly early stage in the improvement analysis process.

Table 14. Guidelines For Further Study of HOV Lane Projects

Cost Effectiveness Indicator	HOV Lane Project Appears to be:		
	Unwarranted ($B/C < 2.0$)	Marginal ($2.0 < B/C < 3.0$)	Warranted ($B/C > 3.0$)
Design Year Peak-Hour HOV Lane Passengers	Below 3,000	Between 3,000 and 6,000	Above 6,000
Base Year Average Freeway ADT Per Lane	Below 12,000	Between 12,000 and 15,000	Above 15,000

Note: Guidelines assume 2.5 percent per year traffic growth rate and $5 million per mile HOV lane capital cost.

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