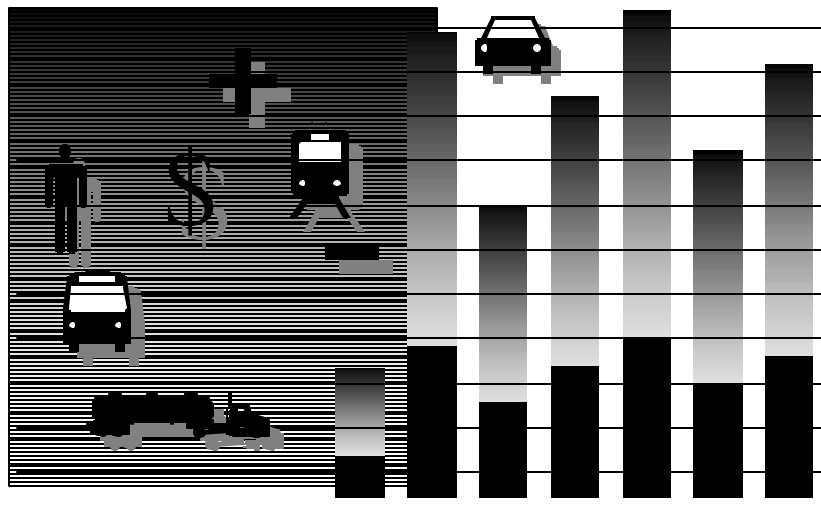




# California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C)

## Technical Supplement to User's Guide



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## **1.0 MODEL OVERVIEW**

### **1.1 GENERAL**

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) offers a simple, practical method for preparing economic evaluations on prospective highway and transit improvement projects within the State of California. The model is capable of handling several general highway projects, such as lane additions, and more specific projects, such as HOV lanes, passing/truck climbing lanes, or intersections. The model can also handle several transit modes, including passenger rail, light rail, and bus. Cal-B/C was developed in a spreadsheet format (MS Excel) and is designed to measure, in real dollar terms, the four primary categories of benefits that result from highway and transit projects:

- Travel Time Savings
- Vehicle Operating Cost Savings
- Safety Benefits (Accident Cost Savings)
- Emission Reductions.

Users have the option of including or excluding the valuation of vehicle emission impacts and induced demand in the analysis. The results of the analysis are summarized on a per-project basis using several measures:

- Life-cycle costs (in \$ million)
- Life-cycle benefits (in \$ million)
- Net present value (in \$ million)
- Benefit-cost ratio (benefits/costs)
- Rate of return on investment (in % return/year)
- Project pay back period (in years).

These results are calculated over the life of the project, which is assumed to be twenty years. In addition, the model calculates and displays first-year benefits.

### **1.2 PROJECT INFORMATION**

Regional or state engineering and planning staff enter project data through the Cal-B/C input sheet. General project information includes the following:

- Project type (i.e., mode)

- Project location (i.e., urban Southern California, urban Northern California, rural California)
- Length of construction period (in years)
- Estimated length of the peak period (in hours).

In addition to the general information listed above, project-specific data serves to define the project more clearly within the Cal-B/C environment. For highway investments, project-defining data consist of:

- Highway design and traffic data:
  - Number of general traffic lanes
  - Number of HOV lanes
  - Estimated free flow speed
  - Length of highway segment and affected areas
- Average daily traffic
- Average hourly HOV traffic
- Three-year accident data for facility
- Statewide accident rates for existing and new highway facility.

For transit investments, project-defining data consist of:

- Annual person trips
- Percent trips occurring during peak period
- Percent trips originating on parallel highway
- Annual passenger miles
- Average vehicles per train
- Transit accident reduction
- Average travel time on transit.

Users also enter a limited amount of information about parallel highway facilities for transit projects.

### **1.3 ECONOMIC ASSUMPTIONS AND VALUES**

Cal-B/C provides all the necessary values and rate tables necessary to proceed with the benefit-cost analysis. The economic values include the following:

- **Real discount rate:** All dollar values used in the model are in constant (currently Year 2000) dollars. Cal-B/C currently uses a real discount rate of 6 percent. This rate is calculated based on the historical real

interest rate and long-term average real rate of return on public fund investments, plus a risk premium to discount all future costs and benefits to the present.

- **Value of time for automobile, truck, and transit passengers:** Current values of travel time used by the model are \$8.16 per hour, \$27.72 per hour, and \$8.16 per hour for autos and trucks, and transit passengers respectively.
- **Vehicle operating costs:** The model provides a look-up table for fuel consumption (in gallons per mile) for autos, trucks, and buses as a function of speed. To calculate total fuel costs, fuel consumption is multiplied by fuel cost per gallon minus taxes (currently \$1.14). Non-fuel costs are estimated per mile (currently \$0.165 per mile for autos, and \$0.285 per mile for trucks).
- **Accident costs:** For highways, the model provides average costs for fatality, injury, and property damage only accidents. For transit, the model provides average costs per fatality, injury, and vehicle damaged.
- **Emissions costs:** The model provides health cost estimates per ton of emissions for CO, NO<sub>x</sub> PM<sub>10</sub>, and VOC.

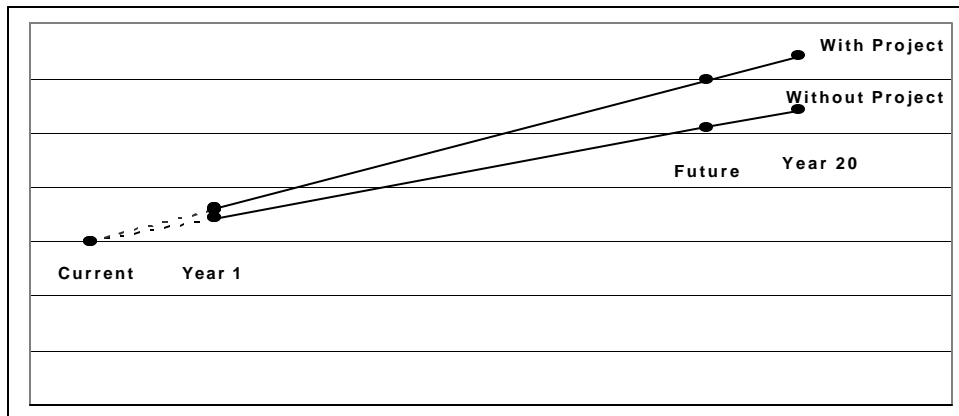
#### 1.4 SPEED AND VOLUME DATA

Cal-B/C calculates the benefits of highway improvement projects as a function of the speed and volume of traffic with and without the project. Speeds and traffic volumes are estimated for the following conditions and are used as the basis for benefit calculations:

- Year 1 with Project
- Year 1 without Project
- Year 20 with Project
- Year 20 without Project.

The model can calculate these values by using simple inputs or accepting data from a regional planning model. The model estimates benefits between Year 1 and Year 20. From the current and forecasted future values for volume and speed, values are estimated for Year 1 and Year 20 using straight-line interpolation, as illustrated in Figure 1-1. The time between the current condition and Year 1 is the construction period.

**Figure 1-1  
Calculation of Values for Year 1 and Year 20**



Project benefits are calculated from the resulting values for Year 1 and Year 20.

#### **1.4.1 REGIONAL PLANNING MODEL AVAILABLE**

If a user of Cal-B/C has access to a regional planning model, the user estimates peak and non-peak speed and volume data using output from the regional planning model for current conditions and two future scenarios:

- Future with Project
- Future without Project.

The current year data are used to approximate the year the project opens. The future scenario year is chosen to be as close as possible to Year 20 after project construction is completed. An average value across affected highway segments is provided for each input.

#### **1.4.2 NO REGIONAL MODEL AVAILABLE**

Some users will not have access to a regional planning model. If the user does not have access to such a model, Cal-B/C estimates the necessary data from simple inputs. The user is able to view the resulting values and override them, if project-specific data are available.

Cal-B/C calculates appropriate speed and volume values using only the seven inputs shown in Table 1-2. All seven inputs should be readily available from

Project Study Reports (PSRs). Year 20 values should be for twenty years after project completion.

**Table 1-2  
Data Used to Estimate Speeds and Volumes**

<b>Input</b>	<b>Current</b>	<b>Year 20 with Project</b>	<b>Year 20 without Project</b>
Average Daily Traffic (ADT)	X	X	X
Duration of congested/peak period	X	Calculated	Calculated
Number of lanes	X	X	Same as current
Free-flow speed	X	Same as current	Same as current

*Calculated - The model would calculate the future duration of the congested period using relationships between speed and traffic volume, which are described later.*

In addition, the user must enter the number of years of construction before the project is completed.

The model calculates appropriate speed and volume data by forecasting volume data for Year 1 with and without the project using straight line interpolation between current and future volumes (as shown in Figure 1-1).

The model separates the current and future ADT data into congested and uncongested volumes using the duration of the congested/peak period (entered by user or 5-hour default value) and an estimate of the percent daily traffic occurring during each peak hour (default is 7.8 percent). On the basis of travel data from the 1991 Statewide Travel Survey, each peak/congested hour is expected to carry 7.8 percent of daily traffic. The model estimates congested volume using the following formula:

$$\text{Volume}_{\text{Congested}} = \text{ADT} * 7.8\% * \text{Congested/Peak Period Duration}$$

Uncongested volumes are calculated as:

$$\text{Volume}_{\text{Uncongested}} = \text{ADT} - \text{Volume}_{\text{Congested}}$$

Speeds are calculated using the standard capacity constraint function, which has been calibrated to the speed volume curves found in the 1997 Highway Capacity Manual:

$$\text{Speed} = \text{Free-Flow Speed} / (1 + 0.15*(v/c)^{10}), \text{ where}$$

v = volume  
c = capacity

The model calculates capacity, c, as:

$$\text{Capacity} = \text{Duration of Congested Period} * \text{Number of Lanes} \\ * 2000 \text{ vehicles/hour}$$

Regional planning models and traffic forecasts occasionally produce volume-to-capacity ratios (v/c) in excess of 1.4. In practice, highways cannot support v/c ratios at this level. The model constrains v/c ratios so they do not exceed 1.4. This ensures that input to the model are reasonable and pragmatic. The maximum v/c ratio is a default parameter that can be changed.

Once the twelve speeds and volumes are calculated, they are displayed for the user to review. The user can choose to accept the values calculated by the model, or enter new values that are project-specific.

## 1.5 LIFE-CYCLE BENEFIT CALCULATIONS

The model estimates the value of four benefits for the project using speed and volume data:

- Travel Time Savings
- Vehicle Operating Cost (VOC) Savings
- Safety Benefits (accident cost savings)
- Emissions Reductions.

These benefits are calculated over a twenty-year life-cycle for the project. The twenty-year period is calculated from the time the benefits begin (i.e., the project opens). Benefits are calculated on an annual basis and summed over the twenty-year period.

The inputs to all benefit calculations are estimates of annual speeds and traffic volumes with and without the project. After values for Year 1 and Year 20 have been calculated, input values for intervening years are calculated using straight-line interpolation:

$$\text{Value}_t = \text{Value}_{\text{Year 1}} + (t/y) * (\text{Value}_{\text{Year 20}} - \text{Value}_{\text{Year 1}}), \text{ where} \\ \text{Value is speed or volume}$$

$$\text{Value}_t = \text{value for benefit calculation}$$

$$\text{Value}_{\text{Year 1}} = \text{value for current year}$$

$$\text{Value}_{\text{Year 20}} = \text{value forecasted for twenty years from beginning of} \\ \text{benefits}$$



- t = year for benefit calculation
- y = number of years from current year to twenty years after benefits begin

### **1.5.1 TRAVEL TIME SAVINGS**

The model follows these steps to calculate estimates of annual and 20-year delay savings on highways:

1. Based on the base and future-year ADT projections, the model estimates future annual ADTs, without and with the improvement project, assuming straight-line growth.
2. Annual ADTs are multiplied by the affected length and then divided by the traffic speed to find the total travel time, without and with the improvement project.
3. Annual travel time savings (the difference between total travel time without and with project) are multiplied by the value of time and average vehicle occupancy for each mode to convert travel time savings into dollar values.
4. The dollar value of travel time savings are discounted to estimate their present value.

The process for transit travel time savings is similar except that annual person trips and total travel time are provided by the user.

### **1.5.2 VEHICLE OPERATING COST (VOC) SAVINGS**

The change in highway vehicle operating costs (increased fuel use, vehicle wear and tear, etc. due to improved speed) are estimated as follows:

1. Estimated future annual ADTs are multiplied by the affected segment length to find annual VMT, with and without the project as well as the difference (VMT savings).
2. For each mode, annual VMT savings are multiplied by the fuel consumption (from look-up table based on average speed) and the unit fuel cost to find the dollar value for fuel VOC savings. Annual VMT savings are multiplied by unit non-fuel VOC to find the dollar value of non-fuel VOC savings.

3. Future annual VOC savings are summed across modes and discounted to obtain their present value.

### **1.5.3 SAFETY BENEFITS (ACCIDENT COST SAVINGS)**

Accident cost savings on the highway are determined as follows:

1. The aggregated accident cost (per million miles) is calculated by multiplying the accident rate by accident cost for each type of accident and summing the result. Transit accident cost savings are calculated similarly, except that the aggregated accident cost is calculated by accident event (i.e. fatality, injury, property damage) rather than accident type.
2. Annual VMT (in million miles) is multiplied by aggregate accident cost (per mile). The result is the annual cost of accidents, without and with the projects.
3. The difference (change in accident cost) is discounted to find the present value of future safety benefits.

### **1.5.4 EMISSIONS REDUCTIONS**

The values of highway emissions reductions are calculated as follows:

1. The aggregate emissions cost (per mile) is calculated by multiplying the emissions rate by the emissions cost for each type of emission and summing the results.
2. Annual VMT (in miles) is multiplied by the aggregate emissions cost. The result is the annual emissions cost, with and without the project.
3. The difference (change in emissions cost) is discounted to find the present value of future emissions benefits.

Value of transit emissions reductions are calculated similarly, except that vehicle-miles (train-miles in the case of passenger trains) are used in place of VMT.

## **1.6 LIFE-CYCLE COST CALCULATION**

Costs for the project are estimated on an annual basis from the beginning of construction to twenty years after the benefits begin. If construction lasts for more than a year, more than twenty years of costs are inputted. For example, if construction lasts five years, project costs are needed for the five years of construction and the next twenty years of project life for a total of twenty-five years of data.

Project costs include:

- Direct costs
- Mitigation costs
- Other costs.

The direct costs include all initial and subsequent project costs:

- Project support
- Right-of-way
- Construction
- Maintenance/Operation
- Rehabilitation.

The values inputted into the model must be denominated in the same dollars as the benefit value tables in the model. The model is currently calibrated to Year 2000 dollars.

## **2.0 VALUE OF TIME**

### **2.1 INTRODUCTION**

An old adage states that “time is money.” In benefit-cost analysis, which provides a common framework for comparing project impacts in dollar terms, this is literally true. Reductions in travel time are frequently the dominant source of benefits for transportation improvement projects.

Highway investments and other transportation infrastructure projects often lead to higher speeds and lower travel times for drivers, passengers, and freight. Since travel time reductions can make-up a sizeable portion of benefits, it is important to use an appropriate value of time when converting these benefits into dollar terms. A low value will understate the benefits of reduced travel time relative to other benefits and costs.

The sections that follow examine several issues concerning the estimation of benefits associated with travel time reductions:

- Factors Affecting the Value of Time
- Theoretical Background
- Methodologies in Use
- Caltrans Methodology.

### **2.2 FACTORS AFFECTING THE VALUE OF TIME**

Theoretical discussions of the value of travel time note that there are two components of the time cost of travel: the resource cost and a disutility cost. The resource cost, or opportunity cost, is interpreted as value to the traveler of an alternative use of time (i.e., work). The disutility cost is interpreted as the general level of discomfort, boredom, or some other negative aspect associated with time lost due to travel. These two components of travel time value suggest that a number of factors affect the value people place on time.

## **2.2.1 RESOURCE COSTS**

In general, the resource costs of travel are influenced by wage rates, trip purpose, and the amount of time saved (or lost).

### 2.2.1.1 Wage Rates

Time values are often measured as a percentage of wage rates. It is generally thought that higher income groups value travel time at a higher price than lower income groups. The United States Department of Transportation (U.S. DOT) guidance on conducting economic evaluation recommends that different wage rates be used as the basis for calculating time values for truck drivers, air travelers, and travelers on surface passenger modes.<sup>1</sup> The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) does not consider air travel, but uses different rates for the other two groups.

### 2.2.1.2 Trip Purpose

As described in further detail later, there is consensus that on-the-clock travel (i.e., work travel) should be valued at the wage rate including fringe benefits, while other trip purposes should be valued at some fraction of the wage rate. Traditionally, commuting time is perceived as having a higher value than travel for personal chores and recreation. However, recent empirical research casts doubt on whether commuting time is actually valued more highly than time spent on other forms of personal travel. Reductions in commuting time are more likely to be spent on personal business or leisure than on earning a wage. If the additional stresses of peak period travel are not considered, travel time should be valued equally for all non-work trips, as recommended by U.S. DOT.

The U.S. DOT does recognize a distinction between local and intercity trips in its departmental guidance on valuing travel time savings. Intercity travel usually occurs in conjunction with expensive services, such as hotel stays, restaurant meals, and entertainment. Since intercity travel time savings can be used for purposes that travelers value highly, intercity trips should be valued more highly than local trips. For most benefit-cost analyses, it is difficult to estimate the number of intercity trips separately from local trips, so a single value can be used for both.

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<sup>1</sup> U.S. DOT. The Value of Saving Travel Time: Departmental Guidance for Conducting Economic Evaluation, April 19, 1997.

### 2.2.1.3 Amount of Time Saved

There has been substantial disagreement in the literature on the value of small units of time. Some studies suggest that small increments of time have lower unit values than do larger increments of time. The rationale is that short time periods cannot be used effectively and that travelers may not even notice them. There is substantial evidence that drivers are often wrong in their own estimates of their travel time. Therefore, changes in travel time of less than a few minutes are of no value.

The counter-argument is that, even though drivers may not accurately estimate their own travel time, they still find uses for an extra few minutes, especially if the time savings are consistent. A further point is that government agencies, evaluating the benefits of improvements, have to take note of cumulative effects. A series of improvements over time, on a given segment or corridor, might well have a non-trivial effect on travel time, although the separate effect of each project is quite small. This issue is addressed in the U.S. DOT guidance paper on time value for benefit-cost analysis.<sup>2</sup> The authors of the U.S. DOT paper valued time savings at the same rate, regardless of the amount of time savings.

## **2.2.2 DISUTILITY COSTS**

In general, the disutility costs of travel are influenced by congestion, passenger versus driver time, and level of service and waiting/walking time.

### 2.2.2.1 Congestion

For short-distance auto travel, the major source of disutility is congestion, presuming that travel under such conditions puts extra stress on the driver.<sup>3</sup> As a result, reductions in travel time during peak periods, which are most likely to be congested, are likely to be valued more highly than reductions in travel time during off-peak periods. Similarly, transit riders may experience disutility from crowded vehicles. However, placing a value on disutility due to congestion can be difficult.

### 2.2.2.2 Passenger Versus Driver Time

Several researchers suggest that the value of time for passengers is lower than that for drivers because they do not have to deal with the stresses of driving.

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<sup>2</sup> U.S. DOT. The Value of Saving Travel Time: Departmental Guidance for Conducting Economic Evaluation, April 19, 1997.

<sup>3</sup> See, for example: Grant, Michael, Analysis of Time Costs for Transportation, Office of Intermodalism, U.S. DOT, 1994.

However, there is disagreement on this point in the prevailing literature. In his 1996 survey, Ted Miller recommends using 55 percent of the wage rate for drivers (all trip purposes) and 40 percent for passengers, whether in autos or transit vehicles (Miller, 1996). On the other hand, the U.S. DOT guidance on travel time recommends 50 percent of the wage rate for both drivers and passengers. While there is not a consensus on this issue, it is logical that the stresses of driving may make travel time savings more important to drivers than to passengers. Unfortunately, the extent of these differences is not well established and should be put aside until they are better researched.

### 2.2.2.3 Level-of-Service and Walking/Waiting Time

There is disagreement about whether distinctions should be made between transportation modes due to differences in comfort and other service attributes. Although some people view transit as less desirable than driving because of reduced privacy and factors affecting comfort, others prefer transit because it frees them from the responsibility of driving and allows for productive use of travel time. Since there is no clear evidence that the disutility of time spent traveling in private vehicles is consistently different from that in transit vehicles, the U.S. DOT recommends using the same value. However, the U.S. DOT does use a higher time value for walking, waiting, and other such actions associated with transit. It is generally accepted that time spent walking and waiting for a vehicle has a higher value to the rider than time spent riding in the vehicle (e.g., exposure to adverse weather).

## **2.3 THEORETICAL BACKGROUND**

Theoretical studies use several methods to estimate an appropriate value of time for travelers. Many studies make a distinction between "on-the-clock" travel and "off-the-clock" travel, the distinction being whether one is paid for the time spent traveling. For example, a truck driver is considered to be on the clock, while a commuter is not. The next four sections discuss analytical issues associated with each of these methods. The appendix provides a bibliography of specific travel time studies.

### **2.3.1 ANALYTICAL ISSUES**

Estimating the value of time for highway users is not a simple matter. There is no market for buying and selling time, so assigning a value to time must be done indirectly. Since the early 1960s, economists have devised several indirect methods for measuring the value of time. However, each of the methods

developed so far has serious limitations. The common problem across all methods is the difficulty in isolating time savings from other factors that travelers are considering.

The methods derived to date typically fall into one of four types of analyses:

- Mode choice
- Route choice
- Speed choice
- Dwelling choice.

#### 2.3.1.1 Mode Choice Analysis

Mode choice studies were among the first attempts to place a value on travel time. These studies attempt to do so by comparing a fast, but expensive mode with inexpensive, but slow one. The assumption is that there is a tradeoff between the cost of the modes and the travel time. The difference in cost is presumably equal to the value of the difference in time. Most mode choice studies compare automobiles with some sort of transit.

However, travel time is not the only difference between two modes. For example, an automobile has service characteristics that many consumers find attractive in comparison with transit, such as: comfort, privacy, schedule flexibility, and lack of waiting time. Early mode choice studies have been criticized for failing to take these differences into account sufficiently. Recent studies have tried to separate these effects from the time differential, but it is not clear how successful these efforts have been. Value of time estimates cannot rely on mode choice alone.

#### 2.3.1.2 Route Choice Analysis

Route choice studies attempt to correct for the problems inherent in mode choice studies by focusing on a single mode. However, the underlying methodology is the same – a slow, inexpensive, option is compared with a faster, more expensive option.

In route choice studies, the two options are different routes for a single travel mode. Typically, the comparison is made between a faster toll highway and a slower, free one. An equation is developed which determines the likelihood that a trip-maker chooses one mode over another, on the basis of the travel times and money costs. For example, the High Occupancy Toll (HOT) lanes in Orange County, on State Route 91, allow this sort of comparison. Drivers that do not meet the occupancy requirements are allowed to use the carpool lanes if they pay



a toll. In this case, drivers are paying for travel time savings. A similar comparison could be made between a surcharge express bus and a local bus along the same route. In this case, extra attention needs to be paid to whether other amenities differ.

While route choice analysis is promising, the number of studies using this technique have been limited due to the low number of places where route choice can be tested. In the future, locations like State Route 91 may be able to provide more accurate data using route choice analysis. Since appropriate economic valuation requires an adequate number of cases, route choice studies need to be supplemented by other techniques.

#### 2.3.1.3 Speed Choice Analysis

Speed choice analysis is one attempt to supplement the results of route choice studies. Speed choice analyses are based on the economic assumption that rational, utility maximizing individuals adopt driving speeds that minimize their total trip costs. While travel time is one component of the trip cost, there are other trip costs, such as vehicle operating costs and accident costs. Observations are undertaken to determine individuals' driving speeds under various conditions, and accident costs and operating costs are estimated in each situation. Assuming that all costs are perceived by drivers and that the least cost speed is selected, the perceived time costs can then be determined.

The difficulty with this framework is that perceived accident costs and operating costs must be estimated in order to determine time costs. Unfortunately, accident costs are just as tenuous and uncertain as the time costs they are being used to estimate because they too are not market items. When considered above, the results of these studies must be viewed with skepticism because drivers' perceptions of the accident costs and other costs that they are trading against time are not known.

To the extent that speed choice and route choice studies yield similar values of time, speed choice studies may help to triangulate an appropriate value.

#### 2.3.1.4 Dwelling Choice Analysis

Another approach to travel time estimation involves comparing property values and travel time to work. In theory, increased distance or travel time from an employment center is associated with a decline in property values, holding all other factors constant, such as crime, school quality, etc. These studies assume homebuyers perform a trade-off between the cost of the house and the amount of time required to commute to work. In this form of study, the value of time is

calculated by comparing housing value against the time it takes to reach the central business district.

Some economists have attempted to allow for other factors and isolate the effect of distance from the urban core on dwelling prices, but with mixed results. In today's polycentric cities, distance from the city center is not, in most cases, the distance from the work place. In addition, the increase in two-worker households means there are usually multiple workplaces to consider. Moreover, the growing shortage of green space in urban areas has caused many people to place a higher value on amenities, such as open space, new construction, and on-site recreational clubs. These factors must also be considered when estimating the value of time savings using dwelling choice analysis.

Like speed choice analysis, dwelling choice analysis requires researchers to control for many factors. Failure to control for any of these factors results in biases. Due to these uncertainties, dwelling choice analysis alone cannot be relied upon to provide value of time estimates. However, the results of these studies can be used to corroborate other estimates.

### **2.3.2 USE OF THE WAGE RATE**

Another common method is to base the value of travelers' time on their wages. Under this approach, the value of a person's time is assumed to be the same as his or her earnings. The average hourly wage for an urban region would indicate the average value of time saved on the work trip. The appropriateness of these estimates depends on whether the person is "on-the-clock" or "off-the-clock". These two traveling cases are described in the sections that follow.

#### 2.3.2.1 "Off-the-Clock" Travel

For trips not part of a person's work, the hourly wage rate of each empirical study is treated as a standard against which their estimated value of time is measured. The concept underlying this approach is that travelers' hourly wages give the opportunity cost of their time. If the person could get to work sooner, the time saved would be used for additional work. The person's wage approximates the value of that additional work.

For most people, however, it is simply not the case that a shorter work trip would result in more time working. Few people work in circumstances where they decide unilaterally how many hours they are to work. The working hours are usually fixed in the basic conditions of a job. A reduction in work-trip time is likely to be used for a later departure in the morning, more leisure in the evening, more errands on the way home from work, or some other non-work

use. It may also be used to shift to a dwelling site farther from the job, the worker thus converting the time saving to a lower-priced house or a larger, or in some sense better, house, perhaps in a more desired location.

These problems notwithstanding, there is reason to suppose that the value of a person's time has *some* relationship to that person's hourly earnings. Many researchers have found the percentage of wage rate to be a convenient metric for reporting findings on value of time. The using a percentage of the wage rate provides a way of normalizing study results from different countries and different times so that they can be compared without the distorting effects from wage differences between countries and regions as well as from differing values of money between time periods due to inflation.

Despite the limitations of the four analytical approaches described earlier, studies have found a surprising degree of consensus, when the results are expressed as a percentage of wage. In an examination of the results of twenty studies conducted since 1960, on the value of automobile travel time for work, Miller found that sixteen studies reported values within the range of 50 percent to 75 percent of the wage rate<sup>4</sup>. This result can be taken as support for choice of a time value somewhere in that range.<sup>5</sup>

#### 2.3.2.2 Trucks and "On-the-Clock" Travel

Although there are few studies that specifically investigate the value of "on-the-clock" travel time, there is a general consensus that a driver's wage rate (including fringe benefits) is the right measure of the value of his or her time when highway travel is, itself, part of the person's work. Thus, the average labor cost for truck drivers is an appropriate value of time for truck traffic. Theoretically, the opportunity cost of travel time also includes vehicle costs and inventory and spoilage costs. In order for interest cost on goods in transit to be a factor, time savings would need to be of a magnitude not typically achieved by highway improvement projects. Reliability might matter, both for goods movement and for trucks carrying service personnel (plumbers, electricians, etc.),

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<sup>4</sup> Miller, Ted R., *The Value of Time and the Benefit of Time Savings*, National Public Savings Research Institute, 1996. This work was commissioned by the U.S. DOT Volpe Center in support of the departmental guidance on the value of time. Another value of time study is found in Litman, Todd, *Transportation Cost Analysis: Techniques, Estimates, and Implications*, 1994

<sup>3</sup> It is worth noting that a very recent study, based on consumer statements of preference, and not included in the surveys referred to here, found values of about 20 percent of the wage rate—Calfee and Winston, *The Value of Automobile Travel Time: Implications for Congestion Policy*, *Journal of Public Economics* 69 (1998) 83-102.

but no easily available information helps to value changes in reliability. Also, data on highway reliability tends not to be collected, so it would be difficult to value in a benefit-cost analysis.

## **2.4 METHODOLOGIES IN USE**

Benefit-cost models generally value travel time savings as a percentage of the wage rate. They differ in the level of detail regarding vehicle types, drivers, passengers, and wage rates. The sections that follow briefly review the estimates used by three different benefit-cost models:

- HERS
- StratBENCOST
- STEAM.

The models are consistent in their overall approach, but use slightly different values based on what was current at the time of model development.

### **2.4.1 HERS**

The HERS model uses separate values of travel time for each class of vehicles (e.g., autos, 4-tire trucks, 6-tire trucks, etc.). Heavy trucks (more than four tires) are assumed to be used only for work, so the value of time for heavy trucks equals the actual work value of time, which HERS calculates from wages and benefits, vehicle costs, and inventory costs. Light-duty vehicles are assumed to be used both for work and other trip purposes, so the value of time is computed by taking the weighted average of on-the-clock travel time and off-the-clock time. Non-work travel, including commuting, personal business, and leisure, is valued at 60 percent of the wage rate. This value was chosen based on a review of the literature (Jack Faucett Associates, 1989). HERS values the travel time of auto passengers (other than the driver) at 45 percent of the wage rate.

Travel time values used in the model are shown in Table 2-1 by vehicle type.

**Table 2-1**  
**Travel Time Values by Vehicle Type used in HERS**  
**(1988 dollars per hour)**

<b>Vehicle Type</b>	<b>Auto</b>	<b>4-Tire Truck</b>	<b>6-Tire Truck</b>	<b>3-4 Axle Truck</b>	<b>4-Axle Comb.</b>	<b>5-Axle Comb.</b>
On-the-clock	\$15.20	\$13.48	\$20.42	\$23.34	\$25.94	\$26.09
Off-the-clock	\$8.94	\$8.94	-	-	-	-
% miles off-the-clock	89.7%	57.5%	0%	0%	0%	0%
<b>Weighted Average</b>	<b>\$9.59</b>	<b>\$10.87</b>	<b>\$20.42</b>	<b>\$23.34</b>	<b>\$25.94</b>	<b>\$26.09</b>

*\*Some 4-tire trucks are used for personal travel.*

For autos and four-tire trucks, separate values are used for urban and rural travel (rural hours are valued more highly because average vehicle occupancy is higher in rural areas). Although the model developers note that travelers place a higher value on time spent in delay (due to stress, etc.) than free-flow, the HERS model does not use different values.

#### **2.4.2 StratBENCOST**

The StratBENCOST model uses the same basic travel time costs as used in HERS. Lower and upper estimates were developed by a panel of experts on travel costs convened as part of NCHRP Project 2-18. The consensus estimates from the panelists are presented in Table 2-2.<sup>7</sup>

**Table 2-2**  
**Travel Time Values by Vehicle Type used in StratBENCOST**  
**(1996 dollars per vehicle hour)**

<b>Vehicle Class</b>	<b>Lower Estimate</b>	<b>Median Estimate</b>	<b>Upper Estimate</b>
Automobiles	\$10.97	\$11.78	\$23.36
Buses	\$77.25	\$82.94	\$164.46
5-Axle Combination Trucks	\$30.07	\$32.28	\$64.01

<sup>6</sup> Time values were taken from the Highway Economic Requirements System Technical Report (Jack Faucett Associates, Bethesda, MD, prepared for the Federal Highway Administration, U.S. Department of Transportation, Washington, DC, July 1991).

<sup>7</sup> Ranges established from "Research Strategies for Improving Highway User Cost-Estimating Methodologies, Vol. 1: Draft Interim Report." National Cooperative Highway Research Program (NCHRP) Project 2-18, Hickling Lewis Brod, Inc. Silver Spring, MD. May 1992.

A congestion premium is applied to travel during congested conditions. The congestion premium represents the additional costs travelers are willing to pay to avoid congestion over a certain threshold.<sup>8</sup>

### **2.4.3 STEAM**

The STEAM model uses in-vehicle time from the U.S. DOT Department Guidance.<sup>9</sup> For urban travel that is off-the-clock, the guidance is 50 percent of the wage rate per person-hour for all trip purposes, all surface modes, and all persons, whether passengers or drivers. The authors of the U.S. DOT guidance took the view that there is insufficient basis for differentiating between drivers and passengers or between autos and transit and chose 50 percent for all person time. Out-of-vehicle time is taken from the Federal Transit Administration's 1997 Technical Guidance on New Starts Criteria.<sup>10</sup> On-the-clock travel time is assumed to be 100 percent of the wage rate.

### **2.5. CALTRANS METHODOLOGY**

The literature review suggests that the most complete and authoritative source for valuing travel time savings is the official U.S. DOT guidance on the subject, issued in 1997.<sup>11</sup> This guidance suggests that on-the-clock (truck) travel be valued at 100 percent of the wage rate (plus benefits). Off-the-clock travel should be valued at 50 percent of the wage rate for in-vehicle travel, and 100 percent of the wage rate for walking and waiting time.

Cal-B/C generally follows the U.S. DOT guidance for estimating the value of time for trucks and off-the-clock highway travel. The value of time for trucks is estimated as 100 percent of the California average Transportation and Utilities wage rate plus benefits.<sup>12</sup> According to the Bureau of Labor Statistics (BLS) the average Transportation and Utilities wage rate was \$18.03 for California in 1996. Between 1995 and 1996, the wage rate changed 2 percent. Using this increase to calculate the wage rate for Year 2000 and adjusting for benefits yields a value of time for trucks of \$27.72.

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<sup>8</sup> *Small, Kenneth A., et. al., Socio-Economic Attributes and Impacts of Travel Reliability: A Stated Preference Approach, University of California, Irvine, California PATH Research Report, UCB-ITS-PRR-95-36, November 1995.*

<sup>9</sup> *U.S. DOT. The Value of Saving Travel Time: Department Guidance for Conducting Economic Evaluation, April 9, 1997.*

<sup>10</sup> *Federal Transit Administration. Technical Guidance on Section 5309 New Starts Criteria. Washington, D.C., September 1997.*

<sup>11</sup> *U.S. DOT. The Value of Saving Travel Time: Department Guidance for Conducting Economic Evaluation, April 9, 1997.*

<sup>12</sup> *According to the American Compensation Association, the value of all benefits are equal to approximately 42 percent of salary.*

The value of off-the-clock highway travel is calculated at 50 percent of the wage rate. According to the BLS, the all-California average wage rate was \$14.43 in 1996. Between 1995 and 1996, this average wage changed 3.1 percent. Using this increase to adjust the wage rate to Year 2000 and multiplied by 50 percent yields a value of time for highway travel of \$8.16 per person. Due to the difficulty in measuring the value of stress due to congestion, Cal-B/C follows the U.S. DOT methodology and ignores any potential difference in the value of time per individual between peak and non-peak periods. However, the model does multiply the value of time by the average vehicle occupancy (AVO).

Cal-B/C provides default AVO figures based on the 1991 Statewide Travel Survey. The Statewide Travel Survey indicates that the statewide AVO is 1.44 for the entire day and 1.38 during the morning peak period. On the assumption that the morning peak is representative of all peak periods, the model uses a default value of 1.38 for peak period AVO. The Statewide Travel Survey also indicates that approximately 39 percent of all driver trips occur during the peak period. Since the other 61 percent of driver trips must occur during the non-peak period and the AVO for the day must be 1.44, the model uses a default value of 1.48 for non-peak period AVO. Separate figures are provided in the case of High Occupancy Vehicle (HOV) lanes. This methodology is described separately in the description for HOV lanes.

For transit travel, U.S. DOT recommends using 50 percent of the wage rate for the value of in-vehicle travel time and 100 percent for walking and waiting time. However, the value of the disutility associated with transit travel is likely to be lower than that for private vehicles, because transit users may have the ability to spend their time doing something else, such as reading, while riding transit. Miller recommended using 40 percent of the wage rate for in-vehicle time on transit.<sup>13</sup> Rather than require users to estimate in-vehicle time and waiting time separately for transit, Cal-B/C simplifies the methodology and uses 50 percent for all transit travel time (in-vehicle and waiting). The resulting value (\$8.16) is the same as the value used for highway travel time.

The next two sections describe how the model estimates travel time savings for highway and transit projects. For both modes, Cal-B/C assumes that the number of travelers with and without the project are the same, but users can enter different values if they have project-specific information that suggests travelers will make new trips (i.e., induced demand) as a result of the project. For instance, an HOV lane project may induce users to take trips they would normally avoid because of congestion.

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<sup>13</sup> Miller, Ted R, *The Value of Time and the Benefit of Time Savings*, May 1996.

Travel time savings can be calculated only for travelers that had travel times before the project was built (i.e., existing travelers). The model calculates travel time savings associated with existing travelers as the change in travel time multiplied by the number of travelers in the without project scenario.

Induced travelers do not have time savings because they were not making trips prior to the project being built. However, they do receive a benefit for making a trip or they would not be making the trips. The model values this benefit using a standard economic technique – consumer surplus theory.

Consumer surplus is the area under the demand curve and above the equilibrium price. This area equals the amount that customers (travelers) would be willing to pay above what they must pay. The change in consumer surplus is frequently used in welfare economics to estimate the benefit that new customers (travelers) receive. Cal-B/C calculates the value of induced demand as 0.5 multiplied by the reduction in travel time and the number of additional travelers. The model uses travel time as the price of travel since most travelers are not likely to consider accidents, emissions, or operating costs when making decisions. A further discussion of consumer surplus can be found in most standard microeconomic textbooks.

The user can toggle whether the model places a value on induced demand. Cal-B/C **does not** estimate the number of induced travelers (the user must enter this), but it can value the benefit if the user supplies a number.

## **2.5.1 HIGHWAY METHODOLOGY**

The Caltrans model calculates travel time savings for highway users as a function of highway speeds, traffic volume and the value of time. Since speeds vary over the course of the day and for different types of vehicles, benefits are calculated separately for trucks and automobiles as well as for the peak period and the non-peak period, and then summed for the year. Annual benefits are summed across the twenty-year life cycle of the project.

To calculate the number of trucks, Cal-B/C asks the user to input the percent truck traffic. If the user is unable to supply information specific to the project, the model uses a default value of 9 percent, which was calculated from the 1998 California Motor Vehicle Stock, Travel and Fuel Forecast.<sup>14</sup> Vehicles with a gross vehicle weight under 8500 pounds are included as automobiles.

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<sup>14</sup> California Department of Transportation, *TSIP*, 1998 California Motor Vehicle Stock, Travel and Fuel Forecast, November 1998.



For each period by vehicle type, benefits are calculated using the following formula:

$$\text{Value of Time Savings} = \text{Value of Time} * (\text{Travel Time}_{\text{Without Project}} - \text{Travel Time}_{\text{With Project}}).$$

Travel time with and without the project are calculated using the appropriate speed and ADT for the period and vehicle type:

$$\text{Travel Time} = \text{Affected ADT} * (\text{Affected Length} / \text{Speed}).$$

The affected length is the length of the highway that is affected by the project. This length is generally the same as the length of the highway segment.<sup>15</sup>

## **2.5.2 TRANSIT METHODOLOGY**

The evaluation of transit projects must consider the travel time benefits that occur on transit, as well as the travel time improvement that may be experienced by highway users who shift modes to transit. Whether the transit project involves bus, light rail, or passenger train modes, the travel time calculations are essentially the same.

The objective is to estimate the travel time costs or savings that result from the proposed project. For each year, travel time is broken down into peak period and non-peak period and the benefits are summed. Travel time benefits are calculated for two user groups:

- Existing transit riders
- New transit riders that came from a parallel highway.

Travel time benefits for existing transit riders are calculated as the difference in travel times multiplied by the number of existing riders and the value of time.

For new transit riders that came from a parallel highway, the benefit is calculated based on the travel time difference between the highway and transit for the with project scenario. If the difference in travel time is negative (i.e., the travel time is smaller on the parallel highway than on transit), the benefit is assumed to be zero. The new transit riders must have shifted models for reasons other than travel time savings. Assuming that these new riders are rational in their decision making, the sum of these benefits must be positive. Since Cal-B/C is unlikely to

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<sup>15</sup> For passing lanes, the model adds three miles as described in the passing lane methodology.

capture all of the benefits (e.g., the value of reducing ones stress by not having to drive, the improved reliability of transit, etc.), the model conservatively estimates that the new transit riders do not receive a benefit.

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## **APPENDIX: BIBLIOGRAPHY OF TRAVEL TIME LITERATURE**

This list includes citations for travel time studies (based on mode choice, route choice, speed choice, dwelling choice, and other study approaches), as well as papers that provide literature reviews and recommendations for the use of specific values.

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## 3.0 VEHICLE OPERATING COSTS

### 3.1 INTRODUCTION

Vehicle operating costs refer to costs that **vary with usage** and are measured per vehicle-mile. Operating costs may include: fuel, tires, maintenance and repair, and mileage-dependent vehicle depreciation. Costs that do not vary with usage, such as insurance, storage, financing, and time-dependent vehicle depreciation, are not included in this definition of operating costs.

Transportation projects can affect vehicle operating costs directly by improving operating conditions or indirectly by influencing traveler behavior. The savings depend on the type of project, but may include improvements in roadway design and traffic conditions (e.g., fewer changes in speed, reduced grades, smoother pavements, and wider curves) or changes in trip characteristics (e.g., more frequent usage and more direct routing).

In a benefit-cost framework, vehicle operating costs, along with time, accident costs, and environmental costs form the traditional group of user benefits that influence cost effectiveness. Although operating cost savings for highway vehicles are calculated as a user benefit for highway projects, operating costs for transit vehicles are typically incurred by agencies and treated as project-specific operating and maintenance costs for transit projects.

The subsequent sections examine the following issues concerning vehicle operating costs in benefit-cost analysis:

- Factors Affecting Vehicle Operating Costs
- Theoretical Background
- Methodologies in Use
- Caltrans Methodology.

## **3.2 FACTORS AFFECTING VEHICLE OPERATING COSTS**

The factors that affect vehicle operating costs (VOC) on highways generally do not vary by type of road. Highway vehicle operating costs are measured in terms of dollars per vehicle-mile and are affected by the following factors:

- Vehicle Type
- Vehicle Speed
- Speed Changes
- Gradient
- Curvature
- Road Surface.

These factors and those that affect transit vehicle operating costs are addressed in detail in the sections that follow.

### **3.2.1 VEHICLE TYPE**

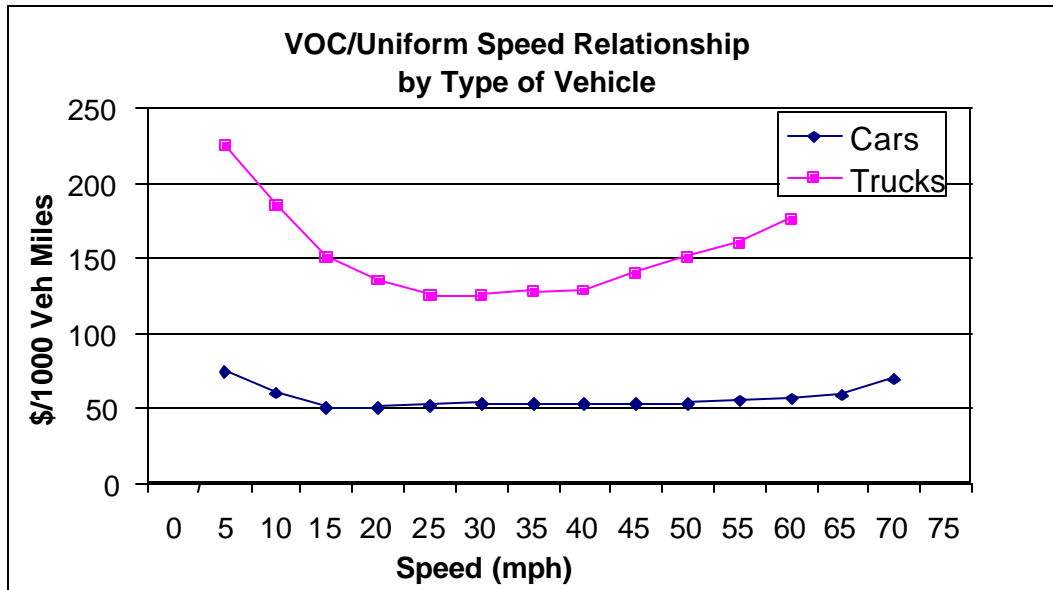
Vehicle operating costs obviously depend on size, class and other vehicle characteristics. Generally, cars have lower operating costs than trucks, due to lower fuel and oil consumption, and lower price of vehicle and parts, maintenance and repairs. Since vehicle technology, fuel efficiency and price/costs change over time, VOC for various classes of vehicles will also change and must be periodically updated.

### **3.2.2 VEHICLE SPEED**

Empirical research indicates that vehicle operating speed is the dominant factor in determining VOC. Graphically, VOC decreases as vehicle speed increases, reaching an optimum efficiency point at mid-range speeds, after which point costs will increase as vehicle speed increases further. Figure 3-1 shows this "U" shaped pattern of the relationship between VOC and uniform vehicle speeds.



**Figure 3-1**



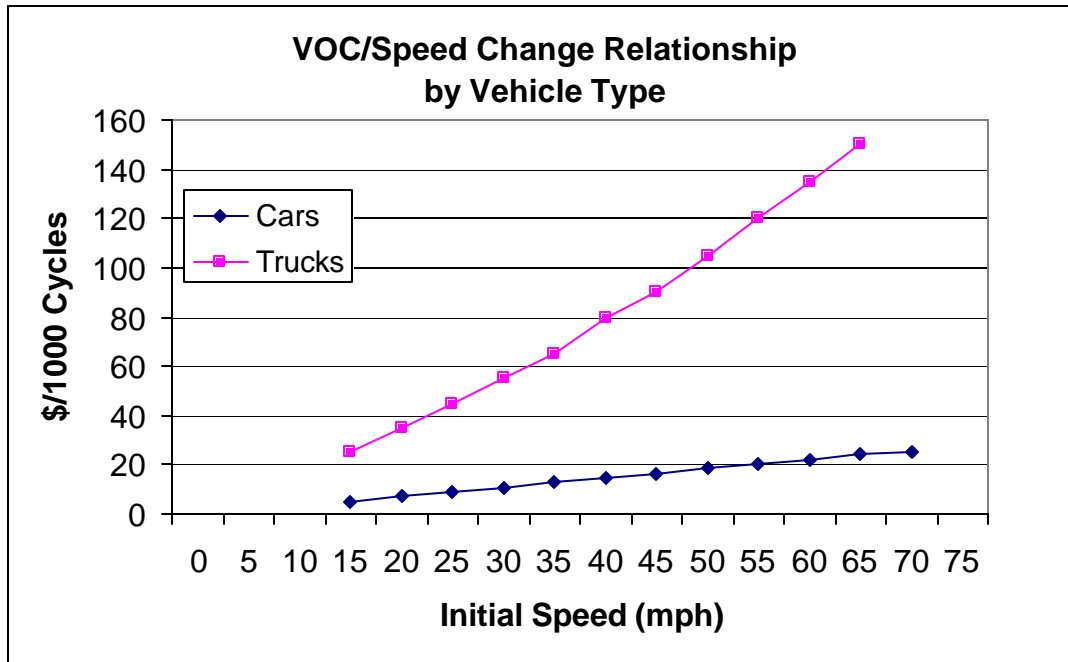
Source: Highway Economic Evaluation Model (Caltrans, 1974)

The implication is that many roadway improvement projects that enable motorists' driving speeds to increase beyond the mid-range may also increase VOC, which would result in negative VOC savings (dis-savings).

### **3.2.3 SPEED CHANGES**

Empirical research also indicates that there is an added vehicle operating cost associated with changing speed (i.e., speed cycles). Further, the added cost of speed cycling is higher at higher speeds, as shown in Figure 3-2 on the following page.

**Figure 3-2**



Source: Highway Economic Evaluation Model (Caltrans, 1974)

### **3.2.4 GRADIENT**

The cost of operating a vehicle is also affected by the gradient of the roadway. Grades may be positive or negative. Driving a vehicle up a steep, positive grade requires more fuel than driving it along a level road at the same speed, and the additional load on the engine imposes added costs of maintenance. Roadway sections with negative gradient would have an opposite effect. However, as the steepness of the down grade increases, it may be necessary to apply the brakes and this also imposes an added operating cost burden.

### **3.2.5 CURVATURE**

Curves impose costs through the centrifugal force that tends to keep the vehicle following a tangent rather than a radial path. The force is countered by superelevation of the roadway and the side friction between the tire tread and the roadway surface. As a result, there is a greater usage of energy, hence more fuel is required to negotiate curved sections. In addition, the side friction increases tire wear and raises this component of operating costs.

### **3.2.6 ROAD SURFACE**

The motion of a vehicle on a rough surface meets with greater rolling resistance, which requires more fuel consumption compared to traveling at a similar speed on a smooth surface. The roughness of road surface contributes to reduction of speed, additional tire wear and influences the vehicle maintenance and repair expenses incurred in the operation of a vehicle. Other elements such as roadway dust also cause extra engine wear, oil consumption, and maintenance cost.

While the effect of roadway grade and curvature on VOC can be empirically evaluated (see, for example, AASHTO "Red Book"), the wide variation in actual surface conditions may complicate the estimation of the pavement factor. There are also other factors that influence VOC, such as potholes, mud, washboarding, and erosion. The effect of such factors, however, can not be generalized in a useful way and are usually left out of most benefit-cost analyses.

### **3.2.7 FACTORS AFFECTING TRANSIT VOC**

The factors mentioned above generally apply to private automobiles and trucks as well as to transit vehicles. Operating costs for transit vehicles (i.e., buses and trolleys) are also affected by other factors, such as transit schedules and vandalism, which are functions of passenger demand. Unless highway projects are sufficiently large to effect travel mode choices, they are unlikely to influence transit vehicle operating costs. For the purposes of analyzing the benefits and costs of highway projects, transit vehicles and other vehicles on the highway are treated similarly.

Another, related, set of factors influencing operating costs for transit vehicles include: the degree of restricted right-of-way, track design, noise restrictions, driver characteristics, as well as prices for fuel, oil, tires, and vehicle parts and services.

However, vehicle operating costs for rail vehicles are incurred as operating and maintenance costs by transit agencies, rather than costs borne directly by users. In a benefit-cost framework, changes in these costs are modeled as changes in project costs, rather than benefits. An analogy in the highway setting is changes in the cost of roadway maintenance.

Vehicle operating costs refer to costs borne by individual transportation users. Modeling highway VOC is more important for highway projects, but may also be necessary for rail projects. If a rail project impacts highway users along the same corridor, the changes in highway VOC should be included in the benefit-cost analysis. Changes in highway VOC form the basis of operating cost user benefits for both highway and rail projects.

### **3.2.8 SUMMARY**

Many factors can influence highway VOC. Modeling all of these factors requires a considerable amount of data collection and analysis. A primary issue for benefit-cost modeling is determining the appropriate level of complexity. For many projects, detailed data are not available and the potential increases in model accuracy are not worth the costs of collecting these data. Estimating VOC benefits can be as simple as using a fixed cost-per-mile figure multiplied by an estimation of traffic volume or using a lookup table showing the relationship between VOC and speed. A more complicated approach is to take into account the individual influences of roadway gradient, curvature, pavement characteristics, speed, and speed changes on each component of vehicle operation (i.e., fuel, oil, maintenance, mileage-related depreciation), and vary these according to the types of vehicles in use.

An additional issue is the estimation of a consumption rate for each component of VOC. Vehicle operating costs are effected not only by the cost of expendable items, such as fuel, but also by how quickly they are used. The consumption of expendable items is related to the factors listed earlier. While many benefit-cost models implicitly use static estimates of consumption rates, consumption rates are expected to change over time. For example, automobile fuel efficiency has improved dramatically over the last two decades. However, the estimate of static rates is reasonable given the unpredictable nature of future consumption. Consumption rates will be updated as more recent data become available.

### **3.3 THEORETICAL BACKGROUND**

This section recent theoretical research on vehicle operating costs. The discussion is organized around four primary topics:

- Modeling Methodology
- Fuel Consumption Rates
- Values for Other Vehicle Operating Costs
- Rail Projects.

#### **3.3.1 MODELING METHODOLOGY**

The data required and modeling complexity necessary to include all of the many factors that affect VOC is not justified by the relatively small gain in the overall accuracy of results. Many sources have noted that the dominant factors contributing to VOC are vehicle type and speed.<sup>16</sup> Although factors, such as pavement surface, can have

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<sup>16</sup> See the technical documentation for StratBENCOST, and the NCHRP 7-12 Technical Memo.

important effects on VOC, estimation is difficult. To estimate the effect of pavement surfaces, one would need to make assumptions regarding the smoothness or roughness of the pavement in both the build and no-build scenarios, over a twenty-year period. Such estimations are clearly beyond the capabilities of most forecasting methods. The modeling complexity found in many benefit-cost models, such as the HERS, StratBENCOST, and RailDEC, is more than necessary. Until the ability to capture the contribution of other cost factors is simplified, estimating vehicle operating costs should be based upon speed and vehicle type.

The STEAM model, which separates the fuel component from other VOC components, provides a good methodology. In a review of VOC models in use around the world, Bein (1993) notes that “fuel consumption and speeds can be readily measured by tests” (pg. 29), and may therefore be more reliable than estimates of the other components of VOC. In STEAM, fuel consumption rates vary according to speed (rather than varying cost estimates), and then a per gallon cost is applied to this result. The remaining components of VOC are estimated as a fixed amount. This methodology allows the user to change the model’s fuel cost prices easily (which tend to vary substantially), without having to re-estimate consumption rates. This method also allows fuel consumption rates to be updated in the event that future research provides better estimates. The remaining components of VOC (oil, tires, maintenance and repair, and depreciation) can be estimated using a fixed cost-per-mile figure, that varies according to vehicle type.

### **3.3.2 FUEL CONSUMPTION RATES**

With the exception of STEAM, most benefit-cost models rely on the same underlying work for component consumption rates and costs. The MicroBENCOST model derived its data from the 1982 study for the FHWA by J. P. Zaniewski et al., *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*. StratBENCOST and RailDEC cite their sources as HERS (for component costs) and NCHRP 7-12 (for consumption rates). NCHRP 7-12 was the project that developed the MicroBENCOST model, and the HERS documentation notes that *their* consumption data were also derived from Zaniewski et al.

The reliability of the estimates derived by the Zaniewski et al. study have been strongly questioned by Bein and Biggs (1993). Their study, carried out in Canada during the late 1980s and early 1990s, compared the Zaniewski et al. work to other state-of-the-art models in use, particularly the ARFCOM model developed in Australia. Referring to the Zaniewski et al. study, they note that their

*model of VOC, and any aggregated relationships derived from the data, such as those in HERS, as well as updates incorporated in MicroBENCOST . . . all have a number of deficiencies. The data encode highway, vehicle technology, and operating, and economic conditions*

*typical of the 1970s, which are not adequate to examine questions arising today in highway transportation planning (pg. 120).*

The STEAM model relies on several sources other than the Zaniewski et al. study. For fuel consumption, STEAM utilizes the rates published in the *ITE Transportation Planning Handbook* (1992), which were derived by Caltrans in the 1970s for the HEEM model and published in 1983.<sup>17</sup> Since the Caltrans work was carried out at approximately the same time as the Zaniewski et al. study, it is no more up-to-date, but probably more specific to highway conditions in California.

No significant new work has been conducted on fuel consumption rates to be used in benefit-cost models. However, there has been a substantial amount of work on vehicle emissions (due to the requirements of the Clean Air Act Amendments, ISTEA, and TEA-21), at both the national and state level – particularly in California.

The California Air Resources Board (CARB) has developed a series of computer models called the Motor Vehicle Emission Inventory (MVEI) Models. Individuals involved with CARB’s modeling process have indicated that it should be possible to determine fuel consumption rates from data used by the MVEI model. These rates would vary according to speed and vehicle type, and would have the added benefit of being specific to the vehicle mix in California.

### **3.3.3 VALUES FOR OTHER VEHICLE OPERATING COSTS**

Table 3-1, on the following page, provides a range of estimates used in several benefit-cost models. As noted previously, Bein and Biggs critiqued the work of Zaniewski et al., which forms the basis of most of these models. Bein and Biggs noted that the estimation of VOC components other than fuel were based on data collected over twenty years ago and are deficient. Although Bein and Biggs point to promising work being done on the Australian ARFCOM model, they do not provide estimates that they feel are more reliable.<sup>18</sup>

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<sup>17</sup> See M. M. Hatano et al., *Energy and Transportation Systems, Caltrans Report FHWA/CA/TL-83/08, Washington, D.C.: Federal Highway Administration, 1983.*

<sup>18</sup> *TTI’s documentation for MicroBENCOST, as well as Bein’s review of VOC models cited, both contain high praise for the Australian ARFCOM model. Indeed, the Final Report for the MicroBENCOST model notes that the model may incorporate ARFCOM’s fuel estimates in future revisions. Further Bein (1993) notes that the “ARFCOM model of fuel consumption is an internationally verified world leader suitable for both rural and urban traffic . . .” (pg. 35). Unfortunately, further information on this model is not available.*

**Table 3-1  
Summary of Benefit-Cost Models**

<b>Attribute</b>	<b>STEAM</b>	<b>HERS</b>	<b>StratBENCOST</b>	<b>RailDEC</b>
<b>Costs include:</b>	gas, tires, M&R	gas, oil, tires, M&R, depreciation	gas, oil, tires, M&R, depreciation	gas, oil, tires, M&R, depreciation
<b>Cost varies according to:</b>	speed (for gas only)	speed, speed cycling, grade, pavement condition, and curvature	Speed, speed cycling, grade, pavement condition, and curvature	speed, speed cycling, grade, pavement condition, and curvature
<b>Range, \$/mile (year)<sup>1</sup></b>	\$0.05 - \$0.09 (1994)	~ \$0.18 (1995) <sup>5</sup>	\$0.17 - \$0.32 (1996)	\$0.18 - \$0.31 (1995)
<b>Vehicle types included<sup>2</sup></b>	cars, trucks	2 car types, 5 truck types	cars, trucks, buses	cars, trucks
<b>Source(s)</b>	ITE and USDOT <sup>4</sup>	Zaniewski et al.	HERS and MicroBENCOST (each based on Zaniewski et al.)	HERS and MicroBENCOST (each based on Zaniewski et al.)

<sup>1</sup> The range provided is for automobiles. For most models, the range represents VOC at different speeds, such that the high number represents VOC at the lowest speed (usually 5 MPH) and the low number represents VOC at the most efficient speed (usually between 35 MPH and 60 MPH).

<sup>2</sup> These vehicle types are considered in the user benefits section of the model. Rail VOC may be considered other parts of the model.

<sup>3</sup> M&R refers to maintenance and repair.

<sup>4</sup> These sources are listed in the description of the STEAM model, section 4.1 above.

<sup>5</sup> HERS calculates a range of estimates that vary according to many factors. Our source for HERS update information provided only the single estimate.

On the basis of that critique, the STEAM model appears to have the best fixed-cost estimates, but with some caveats. STEAM uses a fixed cost-per-mile of \$0.034 for automobiles and \$0.10 for trucks, which include tires, and maintenance and repair costs. The STEAM model does not include mileage-based depreciation, which should also be included in VOC estimation. The model also ignores changes in vehicle operating costs since 1982.

Jack Faucett Associates derived depreciation estimates for automobiles in a 1991 study for the FHWA. These estimates incorporate the increase in lifetime mileage that have resulted from increases in average vehicle age. The estimates also represent a wider group of vehicle classes than in previous studies. Depreciation values from this study are shown in Table 3-2.

**Table 3-2  
Vehicle Depreciation Estimates (in cents/mile)**

<b>Vehicle Type</b>	<b>Depreciation</b>
Subcompact	8.6
Compact	8.7
Intermediate	10.7
Full-sized car	13.5
Compact pickup	8.7
Full-sized pickup	9.5
Minivan	11.8
Full-sized van	14.2

Source: Jack Faucett Associates, Cost of Owning and Operating Automobiles, Vans & Light Trucks 1991, prepared for the FHWA.

### **3.3.4 RAIL PROJECTS**

As discussed earlier, rail VOC changes from rail projects are generally captured in project maintenance and operating costs estimates. The key issue for estimating highway VOC changes that result from rail projects is determining how many highway users are affected. RailDEC estimates them based on the forecasted decrease in average annual daily traffic (AADT) on the adjacent highway facility. While this method requires information on the parallel highway, it has the advantage that it does not assume that all rail users come from the highway. Calculating VOC savings based on AADT reflect the savings only for those rail users that switch from the highway. By changing the number of highway users, rail projects may also affect highway VOC for users that remain on the parallel highway. Unless the change in the number of highway users is large compared to the total number of highway users, this effect is small and can be ignored.



### **3.4 METHODOLOGIES IN USE**

This section reviews the methodologies for modeling vehicle operating costs in four benefit-cost models used outside of Caltrans. The models are primarily highway-oriented, but one focuses on rail projects. The models are reviewed in terms of:

- Methodology for modeling VOC
- Source for rates and costs applied to each component.

The model methodologies vary by which costs are included, what cost-related factors are considered, and how vehicles types are grouped. Most models include costs for gas, oil, tires, maintenance and repair (M&R), and use-related depreciation. Costs can vary by speed, but many models also consider speed cycling, and highway geometrics, such as curvature and grade. Most models estimate VOC separately for cars and trucks, but one model also considers buses. Unless buses make up a substantial component of highway users on a particular facility, changes in VOC operating costs should not influence cost-effectiveness and can be ignored.

Although the models reviewed estimate cost and consumption rates as of 1994/95, they all rely on data from studies from the 1970s. Most of the models rely on consumption rates and costs derived in a 1982 study for the Federal Highway Administration (FHWA) by Zaniewski et al. of the Texas Research Foundation. One model incorporates work conducted by Caltrans in the early 1970s.

#### **3.4.1 STEAM**

The methodology that STEAM employs separates VOC estimates into fuel and non-fuel components. Default values are included for both of these components in the model, but can be changed by the user. The fuel component considers the effect of speed on fuel consumption for two types of vehicles (autos and trucks), and has fixed fuel consumption for two types of buses (local and express) and two types of rail (light rail and heavy rail, denominated as kilowatt hours per vehicle mile).

The non-fuel component employs a fixed cost-per-mile regardless of speed for auto and truck only. Non-fuel costs include tires and maintenance (use-based depreciation is not included, nor is oil).

The most innovative aspect of the STEAM model is the way in which it handles the fuel component. By calculating the fuel consumption per gallon at the average speed, and multiplying this figure by the cost per gallon, STEAM allows users to vary fuel costs, without having to adjust each of the speed/consumption estimates. STEAM's default

fuel cost values exclude taxes (which, as transfer payments, should not be considered in a benefit-cost model).

Default values for the fuel consumption rates used in STEAM come from the ITE “Transportation Planning Handbook,” 1992. However, these rates were derived from a study published by Caltrans in 1983. Non-fuel VOC are taken from a USDOT publication, “Characteristics of Urban Transportation Supply,” 1992, and are converted to 1997 dollars. These costs originated in the American Automobile Association (AAA) publication *Your Driving Costs*.

### **3.4.2 HERS**

HERS was developed for the FHWA to analyze highway widening, as well as pavement and alignment improvement projects at the national level. HERS uses a fairly complex methodology in which VOC are calculated for seven vehicle types (two types of automobiles and seven types of trucks) as a function of fuel, oil, tires, maintenance and repair, and, mileage-based depreciation. The process is done in three steps, using a variety of equations for each step:

- 1) Constant speed VOC are calculated as a function of average speed, average grade, and pavement condition
- 2) Excess VOC (those that occur above the constant speed VOC) are calculated as a function of speed cycling
- 3) Additional excess VOC are calculated as a function of road curvature.

The cost estimate procedures used in HERS were revised in 1997. However, the model relies upon consumption rates and cost values that were originally derived in a 1982 study by Zaniewski et al. of the Texas Research Foundation for the FHWA.

### **3.4.3 StratBENCOST**

In the StratBENCOST model, VOC are calculated by obtaining a consumption rate according to vehicle type (auto, truck, or bus) and grade, for each component (fuel, oil, tire wear, maintenance and repair, and depreciation). Total VOC for each component are found by applying an equation that includes facility length, traffic volume, a value for excess VOC (obtained through a separate equation), and the relevant component cost. These values are each multiplied by a pavement adjustment factor, and finally summed across components for the base and alternate cases. The difference between the two cases yields VOC savings.

The values for VOC component costs are derived from the *HERS Technical Memo*. As noted above, the values for HERS originated with the 1982 Zaniewski et al. study. VOC consumption rates and excess costs are from the National Highway Cooperative Research Project (NCHRP) 7-12, which developed MicroBENCOST.

### **3.4.4 RailDEC**

RailDEC estimates highway VOC benefits by considering forecasted decreases on the highway adjacent to the new or improved rail facility. RailDEC calculates VOC by incorporating costs for fuel, oil, and tire consumption, maintenance and repair, and depreciation. The costs of consumption for each of these components is calculated for the base and alternate cases. For each component, the excess costs due to speed cycling are added to the basic per mile consumption costs. RailDEC determines the number of cycles per 1,000 miles based on a vehicle/capacity ratio for the given highway facility type, taken from a lookup table.

Values for VOC component costs are derived from HERS. Values for excess costs are drawn from NCHRP 7-12 (MicroBENCOST).

## **3.5 CALTRANS METHODOLOGY**

The methodology for the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) was developed to be simple and based upon the most recent, available data. The accuracy of a more complex model would likely be offset by the resources needed for gathering and estimating data.

### **3.5.1 VOC METHODOLOGY**

The methodology used in Cal-B/C is similar to that found in STEAM, which separates fuel operating costs from non-fuel VOC. Among the components of VOC, the relationship between fuel consumption and speed is the most widely understood and modeled. Since fuel rates are separated from other costs, fuel prices (minus taxes) can be updated without altering consumption rates. Moreover, consumption rates can be updated as revised estimates become available.

Fuel consumption data are based on estimates of average consumption for the year 2000, obtained from the California Air Resources Board's Motor Vehicle Emission Inventory (MVEI) models, and on consumption by speed relationships, modeled in HEEM. The fuel consumption rates used in Cal-B/C are shown in Table 3-3.<sup>19</sup> The model looks up the appropriate fuel consumption rate based on speed for each project year.

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<sup>19</sup> The model uses a table interpolated to one mile per hour accuracy.

**Table 3-3  
Fuel Consumption Rates (in gallons/mile)**

<b>Speed</b>	<b>Auto</b>	<b>Truck</b>
5	0.182	0.310
10	0.123	0.181
15	0.089	0.135
20	0.068	0.118
25	0.054	0.120
30	0.044	0.133
35	0.037	0.156
40	0.034	0.185
45	0.033	0.223
50	0.033	0.264
55	0.034	0.316
60	0.037	0.374
65	0.043	0.439
70	0.052	0.511

Consumption rates are converted into the fuel consumed using an "affected vehicle miles traveled," calculated as the length of the corridor (or distance where traffic is affected in the case of passing lanes) multiplied by average daily traffic (ADT). These daily estimates are converted into annual estimates by multiplying by 365. The result is multiplied by the fuel cost. This calculation is performed separately for each year of the project.

The model currently uses \$1.14 per mile, which is the WEFA estimate for fuel costs in 2000, converted to year 2000 dollars using the GDP deflator. WEFA fuel cost estimates are reported in the California Motor Vehicle Stock, Travel, and Fuel Forecast. Cal-B/C uses a fixed cost-per-mile estimate, with a separate estimate for cars and trucks.

Non-fuel cost estimates are based upon those found in the STEAM model plus an estimate for depreciation. The STEAM estimates were updated to year 2000 dollars using the GDP deflator. Automobile depreciation costs are based on values for an intermediate automobile, derived by Jack Faucett Associates in 1991 for the FHWA. Truck depreciation costs are based on values provided by Paccar Inc., the largest truck manufacturer worldwide. Assuming a truck price of \$145,000, annual depreciation of 15 percent, and average annual mileage of 120,000, average annual truck depreciation is 18 cents per mile. Total non-fuel costs are the sum of the STEAM estimate and depreciation estimates updated to the year 2000. Non-fuel cost estimates used by Cal-B/C are shown in Table 3-4. These costs are applied to the change in vehicle miles traveled (VMT) for each year of the project. VMT is calculated as annual traffic multiplied by the length of highway affected by the project.

**Table 3-4**  
**Non-Fuel Cost (\$/mi.)**

<b>Vehicle Class</b>	<b>Cost</b>
Automobiles	\$0.165
Trucks	\$0.285

*In 2000\$*

Highway VOC benefits from transit projects are calculated based upon the forecasted decrease in highway usage and follow the same method used for highway projects.

### **3.5.2 PUBLIC TRANSIT METHODOLOGY**

Rail transit investments may cause highway motorists and bus riders to shift travel modes to rail transit. The net reduction in the number of automobiles and buses on highways as a result of the mode shift leads to a decrease in VOC for vehicles remaining on highways. The potential decrease in highway VOC, caused by a reduction in buses, is negligible and, therefore, is not incorporated into the highway model. All VOC savings to the remaining highway motorists are assumed to come from the reduction in other vehicle (non-bus) traffic.

Transit vehicle operating costs for rail and bus are costs borne by transit operators, and are a component of operation and maintenance costs. Operation and maintenance costs are a component of total project cost – the "cost" part of benefit-cost analysis. Therefore, reductions in transit vehicle operating costs, which may result from the implementation of a transit investment, are not counted as a benefit (i.e., cost savings) by the model. The model accounts only for savings on the consumer side, and not on the operator side. For generalized estimates of transit vehicle operating and maintenance costs, see Transit and Urban Form, TCRP Report 16, prepared for the Transportation Research Board by Parsons Brinkerhoff, Robert Cervero, Howard/Stein-Hudson Associates, and Jeffrey Zupan, March 1996.

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## **4.0 ACCIDENT COSTS**

### **4.1 INTRODUCTION**

An analysis of the cost effectiveness of potential transportation projects should consider possible changes in accident rates. Reducing the number of vehicle accidents is a primary motivation for many highway capital investments or improvement projects. These projects generally derive about one-third of their total benefits from the savings associated with reducing the number or severity of accidents. Rail improvement projects may also lead to accident savings by reducing automobile travel or increasing rail safety. Reductions in the number or severity of accidents on either mode can be converted to an annual benefit, measured in dollars, and included in a benefit-cost analysis.

An assessment of accident savings for proposed highway projects requires an examination of the historical accident rates for the area, or historical rates for the roadway type. For these estimation purposes, accident types can be divided into three broad categories of severity – fatal, injury, and property damage only (PDO). The above accident categories are a simplification of the actual data, which record several levels of injury. On railways, the historical rates for accidents are recorded in terms of the number of total accidents, the number of people killed, and the number of people injured. Differences in accounting lead to somewhat different methodologies for estimating accident values on highways and railways.

In addition to the historical accident rate data, several factors need to be considered when placing economic values on accidents. Accidents can vary in severity and the number of individuals involved. Fatalities result in lost years of life, while injuries result in lost years of productive life. Injuries may also cause pain and suffering. In addition, all accidents result in property damages of varying severity. Although several methodologies exist for placing a value on each of these factors, the analysis is complex. However, estimating these costs accurately is crucial to benefit-cost analysis.

The next sections address the following issues related to accident costs:

- Factors Affecting the Estimation of Accident Costs
- Methodologies In Use
- Caltrans Methodology.

## **4.2 FACTORS AFFECTING THE ESTIMATION OF ACCIDENT COSTS**

Two factors must be considered when estimating the value of accident costs:

- The frequency of accidents
- The value of an accident.

As the sections that follow illustrate, these factors are closely related. Accidents are generally comprised of three events: fatalities, injuries, and property damage. The events that occur determine the severity of an accident. Some agencies report accident statistics by severity (e.g., fatality accident). Other agencies report the frequency with which particular accident events occur (e.g., the number of fatalities). Valuing accidents depends upon how the statistics are reported.

### **4.2.1 ACCIDENT RATES**

The simplest accident statistics describe only the average number of accidents that occur on particular transportation facilities, such as highways and railways. Using these statistics to estimate the probability of accidents ignores other factors that can influence accident rates.

The frequency of accidents can vary substantially by weather conditions, local geography, facility type, facility condition, vehicle class, traffic volume, time of day, driver characteristics, and accident severity. While producing accident rates that reflect every one of these factors would be extremely time intensive, there is a balance between accuracy and simplicity.

Another set of factors associated with accident rates is the number of injuries, number of fatalities, and the amount of property damage involved with each accident. While some agencies report accidents according to the actual number of fatalities and injuries that occur, most state departments of transportation (DOTs) classify highway accidents by severity (i.e., fatality, injury or property damage only). Under this reporting method, accidents are grouped according to the most severe event that occurs. Typically, an accident that results in at least one fatality is reported as one fatality accident, even if several fatalities occurred. An accident that results in fatalities and injuries is reported as a fatality accident, regardless of how many injuries occurred. When accident statistics are reported by severity, the average number of injuries and fatalities associated with each severity category must be estimated.

Other agencies, particularly transit agencies, report accident statistics by the number of events that occur annually. For these agencies, events are defined as accidents, injuries, and fatalities. When accidents are reported in this manner, accident costs are simply the



economic values associated with each event. The average number of events per accident does not need to be considered.

Caltrans reports accident statistics using both methods in the annual *Accident Data on California State Highways* report. However, accident severity statistics are more detailed by facility type than are accident event statistics. Understanding how accident statistics are reported is critical to applying appropriate accident values to them.

#### **4.2.2 BASIS FOR ESTIMATING ACCIDENT LOSS**

Valuing a life lost to a fatal injury requires measuring the potential remaining years of life for accident victims. This loss of years is the essential element of accident cost evaluation.

For non-fatal injuries, the time until functional recovery for the average victim must be estimated, and added to the cost of rehabilitation. To assess the combined loss for injuries and fatalities more accurately, the years lost can be split into several categories, and converted to economic values. These categories include:

- Functional capacity
- Household production
- Wage work.

To estimate loss due to a fatality, years of life lost can be computed by subtracting a person's age at death from the expected life-span as shown in actuarial life-expectancy tables. According to a 1991 Urban Institute study of 1988 highway accidents, the average victim of a fatal highway accident incurred a loss of 42.7 years of life. This future time lost is discounted to a present value (in years). In present value terms, the average fatal injury that shortened a life-span by 42.7 years represents an economic loss of 19.4 years.

Valuing injuries requires measuring their relative severity and aggregating over the years of functional capacity lost to non-fatal injuries. According to the 1991 Urban Institute Study, the average person surviving an automobile crash had 47.2 years of life-span remaining. However, the loss of functioning years was significantly lower, and ranged from 0.01 to 1.85 years, depending on the severity of injuries. The weighted average of the loss of years due to injury accidents is 0.36 present-value years.

An analysis of national highway accident statistics<sup>20</sup> indicate that an average of 1.13 fatalities occur for each fatal highway accident and an average of 1.5 injuries occur for each non-fatal injury accident.

### 4.2.3 METHODS FOR VALUING ACCIDENT LOSS

Over the past three decades several new techniques for economic valuation of non-economic goods have gained credibility and widespread use. These techniques are categorized under four general approaches:

- **Direct costs approach** – This method measures only the easily-measurable out-of-pocket costs of accidents, which include (1) crash clean-up, (2) injury treatment, (3) property repair and replacement, (4) accounting for workplace disruption, and (5) insurance claims processing and related costs. The personal costs, emotional and physical, are ignored in the direct costs method. Another problem is that the medical costs for a serious injury are much higher than for a sudden death. Using only the direct costs yields higher costs for injuries than for fatalities.
- **Human capital approach** – This method does not yield conceptually sound values for use in benefit-cost analysis. The only effects this approach captures are out-of-pocket costs as well as lost work and housework. The human capital method calculates values as a function of salary. As a result, lower values are computed for women and children than for men. This method ignores pain, suffering, and lost quality of life. Human capital costs are useful to determine the dollars lost to injury and death, and form the basis for legal compensation awards.
- **Years lost plus direct costs approach** – This method estimates two sets of costs: (1) the years of life lost to fatalities and the years of productive life lost to nonfatal injuries, and (2) the dollar value of the medical costs. Since the medical costs for a serious injury are much higher than for a sudden death, the combined value is a misleading measure. The years lost method avoids placing a dollar value on lost life and functioning ability. The two values are not additive (dollars plus years), so direct comparisons of proposed projects are not possible. In a comparison of two project alternatives, for example, Project A may have a net cost of \$1 million and save one life annually, while Project B may have a net cost

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<sup>20</sup> Adapted from Federal Highway Administration Technical Advisory T-7570.1 (June 30, 1988)

of \$2 million and save 3 lives annually. Without placing a value on lives, this method does not allow projects to be ranked.

- **Comprehensive method** – This method, also called “the willingness-to-pay-approach,” involves evaluating the reduction of accident risk by estimating the amount people pay for small decreases in safety and health risks, often obtained through the analysis of safety equipment purchases made by individuals. In most instances, such studies show how much people pay to reduce safety risks, but not how much they state they would pay. The comprehensive method places a value on people’s behavior. People exchange money, time, comfort, and convenience for safety. These sacrifices are converted to dollar values, and summed over the user population. Frequently these values are added to the results of the direct cost approach to obtain an overall accident value.

The comprehensive method is the preferred valuation method for benefit-cost and regulatory analysis. Sources recommending this method include the Federal Highway Administration (1988), the National Safety Council (1989), and the U.S. Office of Management and Budget (1989). Since 1986, virtually every Federal regulatory analysis that established the value of reducing accidents and saving lives has used the comprehensive approach.

One recent survey of the theoretical literature found about fifty valid studies that estimated the value of life.<sup>21</sup> Eleven of these studies were specific to automobile safety. In one representative application of the comprehensive method, it was determined that a year of life is worth about \$110,000 more than direct costs. Multiplying this value by the average remaining years of life-expectancy (42.7 years) and calculating the present value results in a value for human life of about \$2.5 million.

The principal weakness of the comprehensive method is the assumption that people make rational decisions about health and safety. Clearly, people do not make rational decisions all of the time. Comprehensive values show the maximum amount that the public should spend to reduce health and safety risks. They do not show how much people should spend to save a known individual from immediate peril. However, values calculated over the entire population result in economically valid estimates. In addition, the value of life estimated by this approach includes the perceived cost of pain and suffering as well as the value of potential lost quality of life.

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<sup>21</sup> Motor Vehicle Accident Costs, *Federal Highway Administration, Technical Advisory Number T7570.2, Washington DC, October 31, 1994*

Ten cost categories, in addition to the value of life, are often included in the estimation of accident costs:

- Pain and suffering (including loss of functional capacity)
- Human capital
  - Personal losses, such as lost wages, lost household productivity, and property damage
  - Other costs, such as legal and court costs, hospital and medical costs, insurance and administrative costs, emergency services costs, vocational rehabilitation costs, workplace costs, and travel delay costs.

The relative values for each of these sub-categories vary depending on the severity of the accident. For example, fatalities incur very high values for lost wages and lost household productivity, but no vocational rehabilitation costs. As the severity of injury declines, the associated costs generally decline, with the exception that the highest hospital and medical costs are incurred by victims of serious, but non-fatal, accidents.

#### **4.2.4 STUDIES OF ACCIDENT VALUES**

Two primary sources exist for estimating the value of the loss associated with accidents:

- 1991 Urban Institute/FHWA study
- National Safety Council.

The primary difference between these sources is that the Urban Institute/FHWA study categorizes accidents by severity (e.g., a fatal accident), while the National Safety Council values the occurrence of particular events (e.g., a fatality). For the purposes of evaluating both highway and rail projects, which tend to report accident statistics differently, the National Safety Council estimates yield the most consistent results.

Despite its age, the Urban Institute/FHWA remains one of the most comprehensive and oft-cited studies of highway accident costs. In a 1995 review of accident cost studies worldwide, Todd Litman relied on the Urban Institute/FHWA study as the starting point for his per-vehicle-mile estimates. Most benefit-cost models use the Urban Institute/FHWA figures as the basis for estimating highway accident costs.

The National Safety Council makes annual estimates of the average cost of fatal and nonfatal injuries due to motor vehicle accidents. These estimates are made using the

comprehensive, or willingness-to-pay, method. The advantage of these estimates is that they are made by event rather than accident type. Estimates by event are particularly useful in estimating the accident costs associated with transit modes.

In 1995, the National Safety Council's estimates of average cost per event were:

- Death - \$2,480,000
- Incapacitating injury - \$137,000
- Non-incapacitating evident injury - \$37,000
- Possible injury - \$20,000
- No injury - \$1,700.

### **4.3 METHODOLOGIES IN USE**

With the exception of the HERS model, most computerized benefit-cost models rely on accident values estimated by the 1991 Urban Institute/FHWA study. The HERS model was released prior to the Urban Institutional/FHWA study. Although most models rely on a common source, some discrepancy exists in how various studies and models have applied the cost estimates. Table 4-1 shows the accidental costs used in four computerized benefit-cost models. Variations in cost are due to update years, update factors, the application of ranges, and the separation of data into internal and external costs.

**Table 4-1  
Accident Cost Estimates**

Accident Type	CSI <sup>1</sup>	StratBENCOST <sup>2</sup>	STEAM <sup>3</sup>	RailDEC <sup>4</sup>
	\$1993	\$1996	\$1997	\$1997
<b>Fatality</b>	\$3,325,095	\$3,521,359	\$2,726,350	\$3,613,137
<b>Injury</b>	\$78,903	\$83,848	\$59,718	\$86,033
<b>PDO</b>	\$5,651	\$5,806	\$3,322	\$5,957

*Note: The HERS estimates are not included, since the model documentation suggests that the 1991 Urban Institute/FHWA estimates are preferred to those used in the HERS model.*

- 1 The costs reported in the Cambridge Systematics, Inc. (CSI) report, Approaches for Developing Nationwide Estimates of Congestion Delay, Accidents, Emissions, and Noise Impacts: Interim Report, 1995. CSI updated the Urban Institute/FHWA figures to 1993 dollars using the consumer price index reported by Bureau of the Census.
- 2 StratBENCOST documentation does not explain how the Urban Institute/FHWA estimates were updated. Although StratBENCOST reports a range of costs, the above figures reflect the middle estimates.
- 3 STEAM documentation does not explain how the Urban Institute/FHWA estimates were updated. Since STEAM reports separate estimates for internal and external costs, the above figures are the total.
- 4 RailDEC documentation does not explain how the Urban Institute/FHWA estimates were updated. Although RailDEC reports a range of costs, the above figures reflect the middle estimates.

Benefit-cost models also differ in the level of detail used to separate accident rates. Table 4-2 illustrates some of the factors models use to identify appropriate accident rates. HERS and StratBENCOST share a common framework that relies on data from the 1991 HERS Technical Report. All models separate accidents into three trips:

- Fatality
- Injury
- PDO.

**Table 4-2**  
**Factors for Identifying Accident Rates**

<b>Model</b>	<b>Number of Accident Types</b>	<b>Facility Type</b>	<b>Traffic Level</b>	<b>Modes</b>
<b>STEAM</b>	3	6	No	Truck, Rail, Bus
<b>HERS</b>	3	10 (5 urban and 5 rural)	Yes	Auto
<b>StratBENCOST</b>	3	12	Yes, Peak and Off-Peak	Auto
<b>RailDEC</b>	3	12	Yes	Rail/Truck Accident Ratio

The four models highlighted in Table 4-2 are described further in the sections that follow.

### **4.3.1 STEAM**

The STEAM model calculates changes in accident costs using accident rates for three accident types (fatality, injury, PDO), for up to six classes of highway facilities, as well as for rail and bus. The accident rates are applied to estimated costs by accident type.

STEAM calculates separate internal and external accident costs. The developers of STEAM have defined internal costs as costs inflicted upon and *perceived* by transportation facility users. External costs are defined as costs inflicted upon users, but *not perceived* by users (i.e., costs that users do not take into consideration when contemplating making trips), as well as costs that are truly external to the user – such as fire and legal costs. While these definitions may differ from standard economic definitions, STEAM is the only model to separate internal and external costs explicitly.

STEAM has default values for both accident rates and accident costs. Default rates are provided for limited-access and non-limited access facilities. The default costs used by STEAM are shown in Table 4-3 in 1997 dollars.

**Table 4-3**  
**STEAM Accident Costs**

<b>Accident Type</b>	<b>Internal</b>	<b>External</b>	<b>Total</b>
Fatality	\$2,317,398	\$408,952	\$2,726,350
Injury	\$50,760	\$8,958	\$59,718
PDO	\$2,824	\$498	\$3,322

These cost figures are based upon the Urban Institute/FHWA study. The developers of STEAM used the 1992 FHWA *Cost Allocation Study*<sup>22</sup> to estimate the external percentage of accident costs and the internal percentage according to the STEAM definitions. The documentation for STEAM states that external costs are approximately 14 percent of total costs. Accident rate data come from the FHWA *Highway Performance Measurement System* (HPMS).

### 4.3.2 HERS

The HERS model, which was developed for the FHWA to conduct benefit-cost analysis at the national level, addresses highway widening, pavement, or alignment improvement projects. Changes in accident costs are modeled as shifts in facility type.

HERS contains accident rates by traffic level and accident category (i.e., fatality, injury, and PDO) for five urban and five rural types of facilities. These rates are combined with estimates of accident costs to obtain the total accident cost for a given facility. HERS contains one value for fatality accidents and ten values each for injury and PDO accidents. The injury and PDO costs vary according to the five urban and rural facility types.

Table 4-4 shows the values that HERS uses for estimating accident costs in 1988 dollars. These values come from a variety of sources, all pre-1990. HERS documentation notes that the 1991 Urban Institute/FHWA study had just been submitted when the model was developed and that the figures estimated in the study should be used once adopted by the FHWA.

**Table 4-4**  
**HERS Accident Costs**

<b>Accident Type</b>	<b>Range for Urban</b>	<b>Range for Rural</b>
Facility	\$2,000,000	\$2,000,000
Injury	\$10,000 - \$18,000	\$17,000 - \$20,000
PDO	\$5,000 - \$6,000	\$4,000 - \$5,000

For incident rates, HERS relies primarily on data from the HPMS, which includes incident rates per million vehicle-miles for each accident type as well as by facility type and traffic volume. These rates were adjusted to account for inconsistencies, and are reported in the *Highway Economic Requirements System Technical Report* (Jack Faucett Associates, 1991). The documentation for HERS recommends that incident rates be

<sup>22</sup> The Cost Allocation Study is undertaken periodically by the FHWA. The study allocates a comprehensive range of highway costs to the sectors responsible for them.



adjusted approximately every two years “to reflect changing national incidence” due primarily to shifts in average speeds.

### 4.3.3 STRATBENCOST

The StratBENCOST model uses accident rates for each of twelve possible facility types. Rates are arranged in tables according to average annual daily traffic (AADT) and peak versus off-peak travel. To estimate accident costs for the base and the alternate case, the accident rate is multiplied by AADT, project length, and the accident cost for each of three accident types (i.e., fatality, injury, and PDO). A minimum and maximum estimate of accident cost is used to generate a range of values for risk analysis. Savings in accident costs due to the facility are estimated as the difference between the base and alternate cases.

Table 4-5 shows the default accident costs used by StratBENCOST. These figures are in 1996 dollars.

**Table 4-5  
StratBENCOST Accident Costs**

<b>Accident Type</b>	<b>Lower</b>	<b>Median</b>	<b>Upper</b>
Fatality	\$809,054	\$3,521,359	\$8,097,408
Injury	\$14,946	\$83,848	\$216,698
PDO	\$1,442	\$5,806	\$11,720

As with other computerized models, the accident cost data for StratBENCOST come from the 1991 Urban Institute/FHWA study. Ranges were developed by an expert panel on accident costs, as part of NCHRP Project 2-18. The calculation of these accident rates is based on the relationships and data presented in the 1991 HERS *Technical Report*.

### 4.3.4 RAILDEC

The RailDEC model was released as a companion to StratBENCOST to estimate accident costs associated with rail, rather than highway, improvement projects. RailDEC is one of few models to estimate the cost effectiveness of rail projects.

The model estimates the reduction in accident costs as the change in the number of highway accidents between the base and alternate case. RailDEC assumes that all new rail trips originated as highway trips in the base scenario. Changes in accident costs are calculated separately for fatal, injury, and PDO accidents. The model allows the mix of accidents to vary by type for rail projects. In addition, estimated accident costs are

multiplied by a rail-truck accident cost ratio, in order to capture additional rail accidents that may occur due to increased rail use in the alternate case.

RailDEC uses a Monte Carlo simulation to generate a distribution of estimates for most variables, including accident costs. Like StratBENCOST, RailDEC reports a range of accident cost savings rather than a single estimate. Table 4-6 shows the default accident costs in 1997 dollars.

**Table 4-6  
RailDEC Accident Costs**

<b>Accident Type</b>	<b>Lower</b>	<b>Median</b>	<b>Upper</b>
Fatality	\$830,140	\$3,613,137	\$8,308,453
Injury	\$15,335	\$86,033	\$222,346
PDO	\$1,480	\$5,957	\$12,026

The accident cost values used in RailDEC are virtually the same as those found in the StratBENCOST model. Both models use cost estimates derived from the 1991 Urban Institute/FHWA study, cost ranges developed by an expert panel for NCHRP Project 2-18, and accident rate estimates originated in the HERS model. While StratBENCOST updates these values to 1996 dollars, RailDEC expresses them in 1997 dollars.

#### **4.5 CALTRANS METHODOLOGY**

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) was developed by Caltrans to evaluate the cost effectiveness of both highway and transit projects. The methodology used in Cal-B/C ensures that accident values are treated consistently across modes.

To estimate the impact of a transportation project on accident costs, Cal-B/C compares accident costs under two scenarios: with the project and without the project. Accident costs are compared over the lifetime of the project, which is assumed to be twenty years. For each year, benefits are calculated as:

$$\text{Accident Benefit} = \text{Accident Cost}_{\text{Without Project}} - \text{Accident Cost}_{\text{With Project}}$$

Accident benefits are summed over the twenty-year period to derive the total impact. Individual projects may improve or adversely impact vehicle accidents, so the net result may be positive or negative.

In valuing the cost of vehicle accidents, Cal-B/C uses costs estimated by the National Safety Council for fatalities and injuries. The National Safety Council data allow accident costs to be computed consistently across modes by using the same value for

individual fatalities and injuries. Although many benefit-cost models rely on the Urban Institute/FHWA figures, these costs are estimated for accidents by severity type (e.g., fatal accidents) rather than by event and cannot be used for non-highway modes.

Cal-B/C uses a variety of sources for property damage costs, since the value of vehicles vary by mode. For each mode, the model uses the best estimate available. The derivation of these estimates are described in separate sections on highway and transit costs.

The impact of a highway project on accident costs is estimated by examining the change in highway accidents as a result of the project. Transit accidents are assumed not to be affected. Since Caltrans has more detailed highway accident data available by severity, Cal-B/C calculates highway costs by accident severity rather than per event.

The impact of a transit project on accident costs is estimated by examining the change on transit and on a parallel highway. Most new transit users are expected to come from the highway as a result of the transit project. This shift effects remaining highway users. The project may also impact the occurrence of accidents on transit.

Transit accident statistics are not available to Caltrans. For transit modes, Cal-B/C uses national accident rates reported by the U.S. DOT. Since these statistics are tabulated by event (i.e., number of fatalities, injuries, and accidents), Cal-B/C calculates the value of transit accidents per event rather than by accident severity.

All accident costs are updated to a common year using the GDP deflator. The model currently uses the following values in Year 2000 dollars:

- Highway accidents
  - Fatality accidents: \$3,104, 738/accident
  - Injury accidents: \$81,572/accident
  - PDO accidents: \$6,850/accident
  
- Transit accidents
  - Fatalities: \$2,710,000/fatality
  - Injuries: \$65,590/injury
  - Property damage: \$61,950/passenger train accident, \$10,750/light-rail accident, \$10,525/bus accident.

The values for highway fatality accidents include the cost of injuries and property damage. The values for highway injury accidents include the cost of property damage.

Details of these estimates and the methodology for each mode is described further in the sections that follow.

#### **4.5.1 HIGHWAY METHODOLOGY**

Cal-B/C calculates the cost of highway accidents by severity:

- Fatal accidents
- Injury accidents
- PDO accidents.

For each accident type, costs are calculated as the cost per accident multiplied by the accident rate and the vehicle miles traveled (VMT) on the facility. The model estimates separate rates for each accident type using three-year historical data for the facility and statewide averages for the facility type found in the *Data on California State Highways* report. This report is published annually by Caltrans.

In the without-project scenario, accident rates are assumed to be equal to the historical averages for the existing facility. The model calculates each rate as the average number of accidents of a particular severity occurring per year divided by the annual VMT.

In the with-project scenario, accident rates are forecast to be equal to the statewide averages for the new facility classification adjusted by the degree to which the current accident rates differ from the statewide averages for the current facility classification.

$$\text{Adjustment Factor}_{\text{Type } i} = \text{Actual Accident Rate}_{\text{Type } i} / \text{State Average Rate}_{\text{Type } i}$$

This calculation is performed separately for each accident type.

The Cal-B/C methodology assumes that a highway with accident rates currently exceeding the statewide average, will continue to do so after the capital project is built. Since some highway investments address safety issues and have the potential to lower accident rates relative to the statewide average, the model gives users the option to adjust accident rates calculated for the future facility.

##### 4.5.1.1 Fatal Accidents

The total value of a fatal accident takes into account the lives lost, the injuries sustained, and the property damaged in the accident.

Using 1995 National Safety Council statistics updated to the Year 2000 by the GDP deflator, the comprehensive value of a fatality is \$2,710,000. This figure includes a measure of the economic willingness to pay for improved safety (the value of lost quality of life), as well as lost wages and other economic costs. According to FHWA Technical Advisory T-7570.1, there are on average 1.13 fatalities for every fatal accident nationally. Therefore, the cost of all fatalities per accident is \$3,062,300.

The average number of non-fatal injuries per fatal accident is assumed to be the average number of injuries per injury accident (1.47) minus the average number of fatalities per fatal accident (1.13). Both figures come from FHWA Technical Advisory T-7570.1. Using 1995 National Safety Council statistics updated to the Year 2000, the average comprehensive cost of a non-fatal injury is \$51,656. After multiplying by 0.34, the average cost of non-fatal injuries resulting from a fatal accident is \$17,563.

This conservative estimate assumes that the total number of injuries (fatal and non-fatal) in a fatal accident is equal to the total number of injuries in an injury accident. The average number of injuries resulting from fatal accidents is likely higher, but this number was unavailable.

The value of property damage resulting from a fatal accident is assumed to be at least as costly as the damages in the most severe injury accidents. Using the 1991 Hickling estimate of the other costs associated with the most severe injury accident updated to Year 2000, property damage for fatality accidents is estimated at \$24,875.

Taking all three components into account, Cal-B/C estimates the total comprehensive value of a fatality accident at \$3,104,738.

#### 4.5.1.2 Injury Accidents

To incorporate varying degrees of personal injuries, the valuation of injury accidents must take into account different levels of severity and their associated costs. Injury accidents can be divided into three categories according to severity:

- Level A Severe (Nonfatal Incapacitating Injury)
- Level B Moderate (Evident Injury)
- Level C Minor (Possible Injury).

Table 4-7 shows the comprehensive value for each injury type estimated in the 1995 National Safety Council statistics. These figures include economic willingness to pay for improved safety, lost wages, and other economic costs. The costs have been updated to the Year 2000 using the GDP deflator.

**Table 4-7  
Comprehensive Injury Costs by Classification**

<b>Accident Classification</b>	<b>Comprehensive Cost per Incident (in \$2000)<sup>1</sup></b>	<b>Number Incidents per Accident<sup>2</sup></b>	<b>Percent Accidents in Category<sup>3</sup></b>
Level A (Severe)	\$149,750	1.21	15.8%
Level B (Moderate)	\$40,450	1.58	51.6%
Level C (Minor)	\$21,850	1.42	32.6%

Sources: (1) National Safety Council, *Estimating the Cost of Unintentional Injuries*, 1995; (2) FHWA Technical Advisory T-7570.1; (3) Hickling and Associates, *Research Strategies for Improving Highway User Cost-Estimating Methodologies* (NCHRP-2-18), 1994

The National Safety Council estimated comprehensive costs per incident. By multiplying these costs by the average number of incidents per accident, the comprehensive cost per accident can be computed. The average number of incidents per accident are based on national figures found in FHWA Technical Advisory T-7570.1.

Finally, an average comprehensive cost per injury accident can be estimated by taking a weighted average based upon the percentage of all accidents occurring in each severity category, as reported in the 1994 Hickling study. The resulting average comprehensive cost per accident is estimated to be \$71,722.

The 1994 Hickling study also estimated the value of the remaining cost categories not accounted for in the comprehensive costs computed by the National Safety Council. These cost categories are split roughly equally between property damage, lost wages, household production, and other direct costs. Other direct costs include legal and insurance costs, rehabilitation costs, as well as emergency and medical costs. After taking a weighted average across severity categories and updating the figures to the Year 2000 using the GDP deflator, the average value of other associated costs are estimated to be \$9,850.

Adding these two components of injury costs results in a total cost per accident of \$81,572.

### 4.5.1.3 Property Damage Only Accidents

Cal-B/C uses a value for PDO accidents estimated by the 1991 FHWA/Urban Institute study. The FHWA/Urban Institute calculated its estimate taking two primary factors into account:

- Unreported accidents - Automobile accident surveys indicate that roughly 40 percent to 50 percent of all PDO accidents go unreported.
- Combined property value - PDO accidents frequently involve more than one vehicle.

The value of an average non-fatal, non-injury accident is calculated primarily using records of vehicle and property damage payments made by insurance companies. Some additional cost categories, such as travel delay and lost wages, make minor contributions to the final estimate.

After adjusting the FHWA/Urban Institute estimate to Year 2000 using the GDP deflator, Cal-B/C uses a value of \$6,850 per reported PDO accident.

## **4.5.2 TRANSIT METHODOLOGY**

The evaluation of transit projects must consider accident savings due to two types of safety improvements. First, transit projects may improve transit safety directly. Cal-B/C estimates this benefit using a percent reduction in accidents supplied by the user. Separate default accident rate values are provided for heavy rail projects, light rail projects, and bus projects. Second, transit projects may improve safety for users of parallel highways as some highway users shift modes to transit and reduce total VMT. Cal-B/C also estimates these benefits.

Total accident benefits for transit projects are calculated using the following formula:

$$\text{Total Accident Benefits} = \text{Net Accident Costs on Parallel Highway} - \text{Net Transit Accident Costs}$$

Each of these two components are discussed in the sections that follow.

### 4.5.2.1 Parallel Highway

Accident impacts for transit projects include potential reductions in accident costs on the parallel highway as highway users shift from the highway to transit. The value of these benefits are calculated in the same manner as for highway projects. Since model users may not know accident rates for parallel highway facilities, Cal-B/C provides the

statewide average highway accident rates for each accident type. The user can adjust these rates if the three-year accident data are known for the parallel highway.

Model users can specify different accident rates on the parallel highway for the with-project and without-project scenarios. In most cases, users can assume that the transit project does not affect accident rates on the parallel highway and simply use the default rates (statewide averages) for both scenarios. Therefore, changes in the number of accidents are due solely to reductions in the number of vehicles using the highway. However, model users can specify different accident rates for the two scenarios, if they have more information.

#### 4.5.2.2 Transit

Cal-B/C calculates transit accident costs as a function of vehicle-miles operated. The model uses default accident rates based on U.S. DOT national averages, since users are unlikely to know accident rates for particular transit facilities. Users may change the default values in the Parameters section of the model.

Separate accident rates are used for each transit mode. Table 4-8 shows the default accident rates used by Cal-B/C.

**Table 4-8  
Default Fatality, Injury and Accident Rates per Million Vehicle-Miles**

Incidents	Passenger Train	Light Rail	Bus
Fatalities	0.24	0.23	0.05
Injuries	0.94	12.8	12.2
All Accidents	1.09	11.13	14.73

Source: USDOT, average of 1994, 1995, & 1996 data

These accident rates are by event rather than accident type. Therefore, the fatality accident rate represents the number of fatalities per million vehicle-miles rather than the number of fatal accidents per million vehicle-miles. For rail modes, train-miles must be converted to vehicle-miles using the average number of vehicles per train.

Since some transit improvements may be safety projects rather than improvements intended to increase ridership or decrease travel time, Cal-B/C allows users to reduce



accident rates. Users are asked to input the percent reduction in accidents that is anticipated as a result of the project.

Since Cal-B/C calculates accident costs as a function of vehicle-miles operated, a transit project that increases vehicle-miles operated (either by extending the system or adding service), but does not improve transit safety will result in a disbenefit for transit accident costs. However, such a project is likely to result in a decrease in accident costs on the parallel highway. Cal-B/C captures both effects.

Total transit accident costs are calculated by multiplying the accident rate by the cost for each incident and summing across incident types. Property damage costs are multiplied by the total accident rate, since all transit accidents result in some level of property damage.

Table 4-9 shows the costs that Cal-B/C uses for each type of transit incident. Cal-B/C uses compatible costs for transit and highway accidents. For both modes, the value of fatalities and injuries are based upon the 1995 National Safety Council estimates. The cost of property damage for transit vehicles are based upon estimates provided by the Federal Railroad Administration, the California Public Utilities Commission, and the Journal of Safety Research.

**Table 4-9  
Fatality, Injury, and Property Damage Costs for Transit Accidents**

Incident	Passenger Train	Light Rail	Bus
Fatality	\$2,710,000	\$2,710,000	\$2,710,000
Injury	\$65,590	\$65,590	\$65,590
Property Damage	\$61,950 <sup>1</sup>	\$10,750 <sup>2</sup>	\$10,525 <sup>1</sup>

Sources: (1) National Safety Council, Federal Railroad Administration, and Journal of Safety Research, Winter 1994 vol. 25 no. 4 p. 193; (2) California Public Utilities Commission 1997, *Annual Report of Railroad Accidents Occurring in California*, Appendix III-C – Light Rail, Rapid Rail and Cable Car Accidents 1997.

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## 5.0 ENVIRONMENTAL COSTS

### 5.1 INTRODUCTION

Transportation investments have consequences for the natural environment. Environmental effects belong to the category of externalities —costs that fall on people other than those who generate them. Environmental externalities are frequently not considered fully in decision-making processes and supporting analyses, such as benefit-cost models. However, environmental impacts from new transportation facilities and increased vehicle use, particularly air pollution and noise, can impose significant costs and, therefore, should be incorporated into benefit-cost models and decision-making processes.

Transportation investments affect the environment because of the construction process, impacts of the facility itself, and resulting changes in travel behavior. Construction activity can affect the environment directly through equipment emissions and noise, or indirectly by causing increased traffic congestion and vehicle emissions during the construction period. The transportation facility itself can destroy or fragment habitat and result in an increase in storm water runoff due to increased pavement. Travel changes, such as increased travel speeds, increased vehicle trip-making, or diversion of trips, have implications for air pollution, greenhouse gas emissions, and noise.

The adverse health effects of vehicle emissions are probably the most significant environmental costs of travel. Enough is known about these effects to incorporate them readily into benefit-cost analyses. Vehicle emissions generally fall into two categories:

- **Air Pollutant Emissions** - Motor vehicles emit pollutants, such as carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), volatile organic compounds (VOC), particulate matter (PM), and oxides of sulfur (SO<sub>x</sub>). These emissions, in turn, can react in the atmosphere to form other pollutants. Ozone is formed through the combination of NO<sub>x</sub> and VOC in sunlight. NO<sub>x</sub>, VOC, and SO<sub>x</sub> can react in the atmosphere to form secondary particulates. Air pollutants can cause damage to human health, building materials, and agriculture and vegetation, as well as limit visibility.
- **Greenhouse Gas Emissions** - Fuel consumption releases gases that trap heat within the Earth's atmosphere, of which carbon dioxide is the most important. Increasing concentrations of greenhouse gases in the

atmosphere may be causing changes in the Earth's climate that could potentially impose substantial costs on society in terms of flooding, crop loss, and increased incidence of disease.

The physical volumes of air-pollutants and greenhouse gas emissions resulting from travel are readily quantified, as the processes that result in these emissions are well understood. A number of researchers have attempted to estimate the health impacts of air pollution in dollar terms. These estimates cover a wide range, but they provide a basis for benefit-cost analysis. As a result, many benefit-cost models include environmental costs resulting from air-pollutant emissions. Information on the effects of greenhouse gases is currently insufficient to support a meaningful range of cost estimates.

Other environmental effects are less significant, less understood, or difficult to quantify and value. As a result, these effects tend to be excluded from benefit-cost models. Ignored effects include:

- **Noise** - Motor vehicles and trains may cause unwanted sounds and vibrations. The costs of noise due to vehicle travel have been estimated, but the estimates vary widely and depend on the specific site of the improvement. Using a standardized set of noise costs for a benefit-cost model is not really feasible.<sup>23</sup> In addition, noise costs are likely to be considerably less than air pollution costs.
- **Hazardous Materials Incidents** - Releases of hazardous materials during transport may impose costs in terms of property damage, evacuations, loss of human life, water pollution, and habitat destruction. However, these costs are relatively small.
- **Upstream Fuel Effects** - There are some negative environmental effects from fuel supply and storage facilities. The accidental release of petroleum products, from leaking pipelines, tanker spills, and leaking underground storage tanks, causes environmental damage to water resources and habitats, as well as human health. These effects are indirectly related to motor vehicle travel since more fuel consumption may increase the likelihood of additional releases. However, these costs are relatively small.

Transportation investments may result in increases or decreases in vehicle emissions. A highway infrastructure project that increases the capacity of a facility may reduce

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<sup>23</sup> A comprehensive review of the subject is provided by Mark A. Delucchi and Shi-Ling Hsu in their 1996 study, "The External Damage Cost of Direct Noise from Motor Vehicles" (complete citation in references section). Delucchi and Hsu define the equations required for estimating noise costs for specific locations. Although noise costs should ideally be calculated in a site-specific manner, the Delucchi and Hsu study and the accompanying technical appendix, provide general estimates by highway functional classification, vehicle type, and urbanized area.

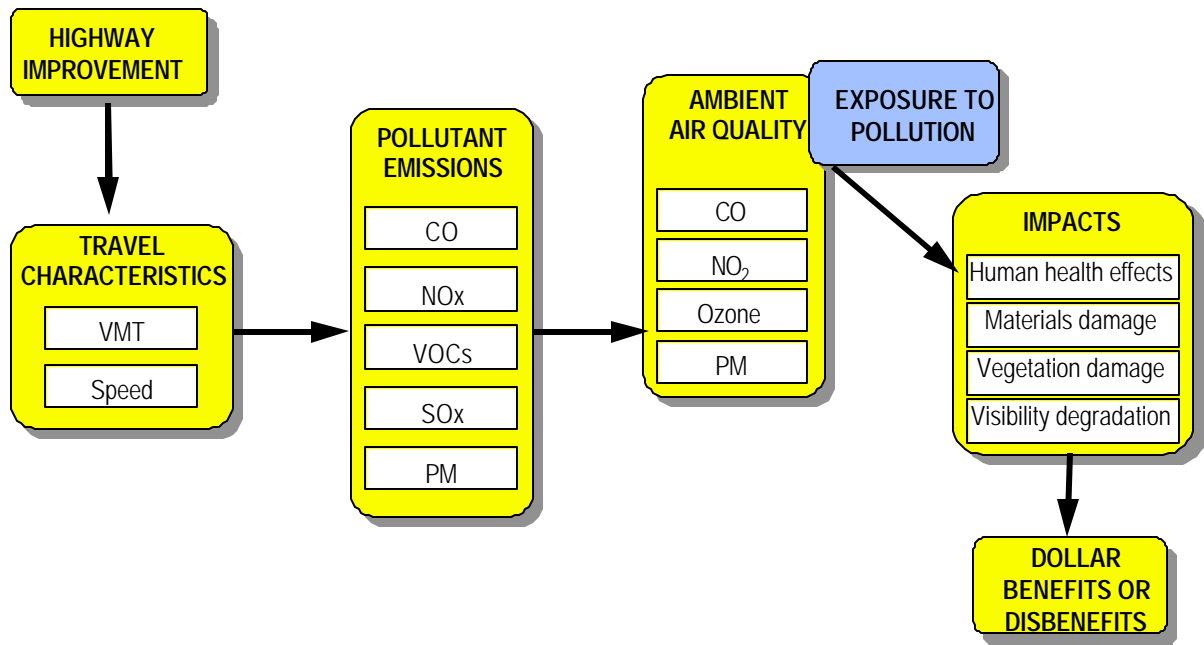
vehicle emissions by reducing congestion, or it may increase emissions by encouraging more travel. Transit investments may also result in increases or decreases in emissions depending on the extent to which increased emissions from transit are offset by reduced emissions from personal motor vehicles. As a result, transportation projects can result in environmental benefits or disbenefits.

The next sections examine the following issues as they concern the evaluation of environmental costs:

- Factors Affecting Environmental Costs
- Estimating the Value of Emissions
- Methodologies in Use
- Caltrans Methodology.

## **5.2 FACTORS AFFECTING ENVIRONMENTAL COSTS**

The following diagram illustrates the analytical process of placing a dollar value on the air-pollution effects of a highway project. In concept, the process is the same for rail transit, although somewhat different in detail. The first three boxes show physical impacts in terms of emissions and their effect on air quality. The next step shows that the impact of changed air quality on human health depends on the degree of exposure. A change in air quality may have a small effect or a great effect depending on the number of people who actually experience the effects caused by the change. Finally, the human health effects are expressed in dollar terms. Most benefit-cost models compress the last few steps and use average dollar values—for the nation, for urban or rural areas, or for specific regions – per unit of emissions.



At each step, there are forces that influence the level of the impact.

### 5.2.1 HIGHWAY INVESTMENT

Highway improvements often reduce, or eliminate, bottlenecks to improve traffic flow and increase average travel speeds. In turn, these effects result in changes in travel behavior. Examples of travel behavior changes include deciding to make new trips, shifting travel modes, diverting to different routes, and traveling during different times of the day. The effects on travel demand and transportation system performance are expected to change over time. However, there may be temporary adverse effects on traffic flow and changes in travel behavior during highway construction.

The extent to which an investment results in changes in travel behavior depends on factors such as:

- Severity of existing traffic congestion
- Type of investment and extent to which it affects travel costs
- Transportation system network (e.g., presence of alternate routes)
- Elasticity of demand for travel.

### 5.2.2 TRAVEL CHARACTERISTICS

The amount of air pollution emitted by motor vehicles depends on the amount of travel, characteristics of travel and vehicles, as well as other factors. The EMFAC model developed by the California Air Resources Board (CARB), is available to estimate and forecast emission rates. Emission rates change over time, as older vehicles are replaced with new vehicles that have improved emissions controls. CARB has also developed

some simple estimates of emissions of power-plant emissions for rail travel. Factors that affect the amount of highway vehicle emissions include:

- Vehicle miles traveled (VMT)
- Number of "cold start" vehicle trips (Starting a cold vehicle results in additional emissions because a vehicle's emissions control equipment has not reached its optimal operating temperature.)
- Mix of vehicles in the fleet (e.g., light-duty gas vehicles, light-duty diesel vehicles, light-duty gas trucks, etc.), and changes in the mix—this allows for the effect of more or fewer trucks or buses.
- Age of the vehicle fleet
- Types of vehicle inspection and maintenance programs in place
- Ambient air temperatures
- Vehicle speeds and traffic flow—Speeds are of particular importance in determining vehicle emission rates. In general, VOC emission rates tend to drop as speed increases, whereas NO<sub>x</sub> and CO emission rates increase at higher speeds (above 55 miles per hour). Emission rates are also higher during stop-and-go, congested traffic conditions than during free flow conditions at the same average speed. However, current emissions models do not address adequately the variations in the drive cycle, for a given average speed.

### **5.2.3 AIR QUALITY**

Air pollutant emissions affect ambient air quality, but the relationship is non-linear for some pollutants. For pollutants like CO that are directly emitted, the change in air pollution concentration can be considered proportional to emissions. For secondary pollutants, such as ozone, the relationship is more difficult to estimate. Some of the factors that influence changes in air quality are:

- VOC to NO<sub>x</sub> ratio - At the margin, ozone formation depends primarily on NO<sub>x</sub> emissions. If the ratio of ambient levels of VOC to NO<sub>x</sub> is high, ozone formation is said to be "NO<sub>x</sub>-limited." If the VOC/NO<sub>x</sub> ratio is low, ozone formation is "VOC-limited," so that reducing NO<sub>x</sub> has a marginal effect and VOC must be controlled.
- Climate and meteorological conditions - Factors such as temperature, sunlight, and wind contribute to air pollution levels. These factors explain why certain areas like the Los Angeles air basin are particularly

susceptible to air pollution problems. High temperatures, sunlight, and low winds tend to increase ozone formation.

- Pollutant dispersion - CO is known to concentrate in small areas (known as "hot spots") near the source. Much of particulate emission comes from road dust resulting from passing vehicles. Controversy exists over the health impacts of road dust, but any effects are largely felt close to roads where dust is thrown into the air. On the other hand, secondary pollutants that are formed in the atmosphere, such as ozone and secondary particulates, tend to spread over large areas.

#### **5.2.4 IMPACTS OF AIR POLLUTION**

Impacts depend, in large part, on the level of exposure to pollutant concentrations. Human health effects depend on human exposure to pollution. As a result, the population within a region is a good index of exposure to pollution for estimating health effects. Similarly, damage to materials tends to be associated with population exposure, since populated areas tend to have more buildings that can fall victim to corrosion. Vegetation damage depends on the level of exposure of crops and forests to air pollution. An area with a high level of agriculture and forests is expected to have greater levels of crop losses and tree harm than areas without these characteristics. Exposure is not an issue for climate change since the effects of greenhouse gas emissions are presumed to be global.

#### **5.2.5 DOLLAR VALUES**

The cost of air pollution depends on the types of impacts that occur. The monetary value of health and environmental damage is not easy to assess. There are a number of factors that affect the dollar value of physical impairment, mortality, or other pollution-damage. In particular, for health-related effects, the severity of the damage, duration of the damage (chronic illness or temporary pain), and age of persons affected influence the value of the damage. For agriculture damage, the value of crops gives dollar value of damage. To quantify the effects related to visibility, it would be necessary to put a value on lost scenic beauty.

### **5.3 ESTIMATING THE VALUE OF EMISSIONS**

The costs of air pollution are typically estimated based either on damage costs or control costs. Damage cost valuation involves estimating the actual value of the harm caused by air pollution, whereas control cost valuation examines simply the cost of the measures necessary to reduce air pollutant emissions.<sup>24</sup> Damage cost valuation is preferable because studies that use control costs to value air pollution rely on the assumption that the controls placed on pollution are efficient. The California Life-Cycle

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<sup>24</sup> *If an emissions trading system is in place, the value of pollution also could be assessed based on the cost of emissions.*



Benefit/Cost Analysis Model (Cal-B/C) uses air pollution cost estimates based on damage estimates developed from a detailed study by McCubbin and Delucchi.

In order to estimate the cost of pollution per ton, a damage cost valuation methodology involves the following steps.

- 1) The impact of pollutant emissions on air quality is modeled/estimated.

Ambient air pollution concentrations are the result of air pollutant dispersion, reaction, and residence, complicated by meteorology and topography. These processes result in non-linear relationships between pollutant emissions and air concentrations, necessitating the use of sophisticated computer modeling. For secondary pollutants, such as ozone, the relationship is particularly complex. These factors explain why certain areas like the Los Angeles air basin are particularly susceptible to air pollution problems. As a result, one ton of VOC may result in more of an increase in ozone concentrations in one metro area than another. Many analysts assume that air pollutant concentrations are linear functions of air pollutant emissions.

- 2) The increase in health problems (anything from headaches to chronic disease and mortality) are estimated based on dose-response functions and a measure of population exposure.

Epidemiological studies have been undertaken to measure the health impacts of exposure to increased doses of pollutants. These dose-response mechanisms are understood fairly well, and dose-response functions can be used to estimate the increased risk of developing a certain adverse health effect (such as headaches, chronic respiratory problems, or mortality) in response to increased air pollutant concentrations. Human exposure to air pollution is also a factor in the value of health effects since more exposure to pollution will result in more health problems. Thus, the value of a ton of pollution in an urban area will tend to be greater than in a rural area because of greater population exposure. Some pollutants, like CO, tend to have localized impacts, while others are regional in scope.

- 3) Dollar costs per health effect are estimated.

Economic dollar valuation of health symptoms and death have been developed and outlined in a variety of literature. There are several general approaches to quantifying health impacts in monetary terms:

- Revealed preferences (estimating costs based on people's behavior)

- Expressed preferences (asking people about the cost of an impact)
- Preferences expressed by jury awards.

Revealed preferences are often used in cases where market prices are unavailable. For example, the cost of increased risk of death from disease related to air pollution does not have a market value per se, but may be estimated by a hedonic pricing study of the higher wages paid in riskier jobs. Regression analysis is used to isolate the additional wage associated with a certain amount of added risk. This is converted into a dollar amount workers appear to demand for each additional increment of risk of death. Workers may be found to require an additional \$1000 for an added 1/1000 risk of death per year, implying a total value of \$1 million per statistically expected death in a large population.

In addition to wage studies, property value studies have been used to quantify the benefits of pollution or noise reduction. Revealed preference studies are widely used for policy analysis, but the resulting estimates have a significant amount of uncertainty surrounding them. If a regression does not consider the appropriate variables affecting wages or house prices, it will incorrectly estimate the effects of pollution. An assumption in these studies is that workers and home buyers have complete information about the risks associated with local pollution and that consumers have reasonable alternatives.

Expressed preferences are an alternative to revealed preferences, and may be measured in contingent valuation studies (a form of survey). In this approach, people are directly asked how much money a certain impact is worth to them. They may be asked how much they would be willing to pay to avoid a day of intermittent coughing that resulted from air pollution, for example. Expressed preferences are a controversial approach to quantifying impacts, but often are used in policy analysis. One problem is that people may claim they are willing to spend a great deal if they know their answers can affect policy and they will not actually have to spend that much money individually. Another problem is that they may not completely understand the impact as described in the survey, and they might be willing to spend more if they really understood the implications of the policy decision in question.

Jury awards are another indication of the value society places on certain impacts. If juries typically award a particular sum for certain types of injuries, an analyst may choose to use that figure as a proxy for the cost to society. However, this approach is not used often and assumes that juries award the actual value of the damage.

Given the large uncertainties associated with each of the steps above, dollar estimates of a given pollutant's value vary widely among studies. In particular, dollar values may vary from one study to another because:

- The relationship between emissions and air pollutant concentrations differs in different regions.
- Exposure to air pollution differs in different regions.
- Different types of health effects are assessed in different studies.
- The values ascribed to specific health effects differ among studies.

## **5.4 METHODOLOGIES IN USE**

Despite potential modeling complexities, transportation benefit-cost models, such as StratBENCOST and STEAM, account for some environmental costs. These models tend to limit their evaluation to emissions effects and ignore other environmental costs. However, the STEAM model provides options to evaluate other environmental costs, such as noise and global warming.

### **5.4.1 STRATBENCOST**

The StratBENCOST model estimates the value of air pollution effects associated with highway investment. Effects are estimated for hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO<sub>x</sub>). The methodology is straightforward.

The model uses lookup tables of emission rates at various speeds for three vehicle types: small vehicles, buses, and trucks. The emission rates tables are taken from those developed in *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors* (Texas Research and Development Foundation, Austin, Texas, Federal Highway Administration, June 1982). Using an estimate of average travel speed, StratBENCOST interpolates between values in the lookup tables to identify unique emission rates for each pollutant for each vehicle type, for both peak and non-peak periods. Vehicle miles traveled are multiplied by emission rates (in grams per mile) for each vehicle class, for each time period, and summed to estimate the total volume of each pollutant emitted. The volume of each pollutant (in tons) is then multiplied by the value of each pollutant (in dollars per ton) to estimate total environmental costs. The value of each pollutant comes from *Monetary Values of Air Pollution Emissions in Various U.S. Cities* (Wang, M. and D. Santini, Transportation Research Board Paper No. 951046, 74<sup>th</sup> Annual Meeting, January 1995).

While the straightforward manner of the approach is good, the StratBENCOST procedure has a number of flaws that cast doubt on the accuracy of its estimates. The

emission rates being used in the model are taken from a 1982 publication that is seriously outdated.<sup>25</sup> Emission rates have fallen significantly over time. Average fleet VOC emission rates are at least 60 percent lower in 1998 than in 1980. Emission rates are projected to continue to decline considerably over the next 20 years.

The study by Wang and Santini used for valuing pollution in StratBENCOST required regression analysis to develop estimates of the value of a ton of emissions in various metropolitan areas. Wang and Santini note that the regression relationships underestimate the value in some regions but overestimate in other areas when compared to the initial estimates. Since the regression relationships rely on original estimates, the authors recommend that when available, original emission values be used. However, StratBENCOST uses the estimates of pollution costs for various cities coming out of the regression analysis for its high, median, and low estimates. This may not be a major flaw given the uncertainty of all the estimates. The analysis fails to account for particulate matter pollution, which recent studies suggest may be a major component of total air pollution health costs.

StratBENCOST also exhibits some weaknesses in its calculation of induced travel and speeds, which in turn affect its pollution calculation. StratBENCOST does not account for peak spreading since it assumes that the number of peak-period hours and percent of average annual daily traffic (AADT) in the peak period are fixed. In reality, the amount of traffic occurring in the peak period is a function of the V/C (volume-to-capacity) ratio. More induced travel is likely fall in the peak period than estimated by the model. Speeds would change correspondingly.

#### **5.4.2 STEAM**

The STEAM model estimates the cost of air pollution effects and provides the option to calculate the value of other external effects like global warming and noise. Since the model uses a network analysis, STEAM is able to calculate emissions more accurately than StratBENCOST by examining both changes in VMT and changes in the number of vehicle trips on the system. In STEAM, emissions for autos, trucks, and carpools are calculated as the sum of mileage-based emissions on the highway system (assuming that vehicles are already warmed up), and emissions due to cold starts are added to get the total. Although the model does account for energy consumption by rail, it ignores emissions due to power plant generation and assumes that rail is free of emissions.

Mileage-based emissions are calculated using emission rates as a function of speed. Emission rate tables contain estimates of emission rates at speeds of 5 to 65 miles per

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<sup>25</sup> According to the documentation for StratBENCOST, Version 1.0, StratBENCOST calculates environmental costs utilizing emission tables developed in *Vehicle Operating Costs Fuel Consumption, and Pavement Type and Condition Factors*. Texas Research and Development Foundation, Austin, Texas, FHWA, June 1982. According to NCHRP, the contractor "has made major strides towards the completion of a revised version of the StratBENCOST software" (<http://www2.nas.edu.trbcrp/68866.html>). The update to the model may include up-to-date emission rates, however, this has not been confirmed.

hour in increments of 5 mph, and the spreadsheet interpolates to get emission rates at intermediate speeds. Average speeds are trip-based (i.e., calculated as origin-to-destination mileage divided by origin-to-destination travel time). Added emissions due to cold starts are calculated on a per vehicle trip basis and are combined with the mileage-based emissions. STEAM allows the user to specify the fraction of vehicle trips starting cold. National defaults are provided from recent research.

Emissions are calculated for three classes of vehicles: autos, trucks, and carpools. Transit emissions are calculated by applying emission rates to changes in transit vehicle miles specified in the inputs. STEAM calculates the costs of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM<sub>10</sub>) by multiplying emissions by a cost per ton for each pollutant. The cost per ton values for HC, CO, and NO<sub>x</sub> come from the same source as used in the StratBENCOST model: *Monetary Values of Air Pollution Emissions in Various U.S. Cities* (Wang, M. and D. Santini, Transportation Research Board Paper No. 951046, 74<sup>th</sup> Annual Meeting, January 1995). However, in STEAM, only the costs for Denver are used, and these are adjusted to 1997 dollars. For PM<sub>10</sub>, costs are taken from the lower-bound estimates in *The Annualized Social Cost of Motor Vehicle Use in the U.S., 1990-91: Summary of Theory, Data, Methods, and Results* (Delucchi, M. Institute of Transportation Studies, Davis, CA, June 1997).

STEAM calculates global warming costs associated with carbon dioxide (CO<sub>2</sub>) emissions from autos, trucks, buses, and rail. The calculation is straightforward. Fuel use is estimated for the base case and improvement case, and an emissions factor in CO<sub>2</sub> tons per million BTU is applied to calculate CO<sub>2</sub> emissions. A user-specified global warming cost per ton of CO<sub>2</sub> is then multiplied by emissions to estimate total costs. A default value for the cost per ton of CO<sub>2</sub> is provided from a study by the Intergovernmental Panel on Climate Change (IPCC), cited in FHWA's *Federal Highway Cost Allocation Study*.

Noise costs are calculated based on a dollar-per-mile cost estimate for autos and trucks for various classes of highways and an average cost per mile for bus and rail. Costs per vehicle mile are taken from FHWA's *Federal Highway Cost Allocation Study* (Appendix E, 1997).

STEAM requires user-specified inputs for many variables. The model includes emission rates for 2010 based on EPA's MOBILE5a emissions model and estimates from E.H. Pechan for PM<sub>10</sub>. If the user wishes to examine impacts in a different year, the user must input emission rate estimates for the relevant year and make adjustments in emission rates based on local factors, like temperatures and the existence of inspection and maintenance (I&M) programs. The documentation notes that fuel consumption rates are based on estimated 2005 urban auto rates (based on Cohn, L., R. Wayson, and Roswell, "Environmental and Energy Considerations," *Transportation Planning Handbook*, Institute of Transportation Engineers, 1992), which appears to be a discrepancy since pollutant emissions are estimated for 2010.

### 5.4.3 VALUE OF EMISSIONS

Air pollution costs vary from region to region. The Wang and Santini study used for cost estimates in StratBENCOST and STEAM provides the cost of a ton of pollution for specific cities.

More recent and extensive cost estimates are available from a study by Donald McCubbin and Mark Delucchi (McCubbin, D. and M. Delucchi. "The Social Cost of the Health Effects of Motor Vehicle Air Pollution." Report #11 in the Series, *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*, Institute of Transportation Studies, University of California, Davis, August 1996.) This study provides a low and high estimate of the cost per kilogram of motor vehicle emissions in 1991 dollars for urban areas and a separate low and high estimate for Los Angeles, which can be used in this analysis. Converted into dollars per ton, the average urban area values are presented in Table 5-1.

**Table 5-1  
Health Cost per Ton of Motor Vehicle Emissions (1991 dollars)**

<b>Emission</b>	<b>Ambient Pollutant</b>	<b>Low</b>	<b>High</b>
CO	CO	9	90
NO <sub>x</sub>	Nitrate PM <sub>10</sub> , NO <sub>2</sub>	1,440	21,200
PM <sub>10</sub>	PM <sub>2.5</sub> , PM <sub>10</sub>	12,500	170,100
SO <sub>x</sub>	Sulfate PM <sub>10</sub>	8,700	82,500
VOC	Organic PM <sub>10</sub> and ozone	140	1,440

The methodology employed by McCubbin and Delucchi, to arrive at these estimates, is extremely detailed and sound. The effect of pollutant emissions was estimated based on modeling the changes in air pollutant concentrations and applying dose-response functions for individual pollutants in order to estimate changes in health effects. For example, the costs associated with NO<sub>x</sub> emissions are associated with damage, which is associated with NO<sub>2</sub> and nitrate particulate matter that forms in the atmosphere. A range of cost values was applied to individual health effects and mortality. The resulting cost values for each pollutant are generally in the range of those of Wang and Santini, with the exception that PM<sub>10</sub> and SO<sub>x</sub> emissions are valued more highly and VOC is valued less highly.

There is some evidence that road dust is not as harmful to human health as emissions of particulate matter from vehicle exhaust, which tend to be fine particles. As a result, a lower dollar value per ton is applied to PM<sub>10</sub> from road dust than from vehicle exhaust

or brake and tire wear. The McCubbin and Delucchi study contains separate estimates of costs of PM<sub>10</sub> (all particles under 10 micrometers in diameter) and particles between 2.5 and 10 microns in diameter. The latter figure is used for road dust. The model uses a mid-range value between the high- and low-estimates for all pollutants. The option for a range is included so that the user can test the results assuming higher or lower emission costs.

The model uses different cost values per ton in different parts of California. The "cost" of emissions depends on exposure to pollution. As a result, the cost of a ton of pollution will be much greater in Los Angeles and other high-population areas than in rural parts of the state. The McCubbin and Delucchi work provides separate estimates of the cost per ton for each pollutant in the Los Angeles area, urban areas as a whole, and the U.S. nationwide.

## **5.5 CALTRANS METHODOLOGY**

The only environmental benefits calculated by Cal-B/C are the value of health effects associated with changes in air pollutant emissions. The user has the option to turn off the calculation of these values. The model does not measure the cost of vehicle noise, since such costs vary widely and are site-specific.

Cal-B/C computes emissions benefits by comparing the value of emissions with and without the transportation project. A transportation project could yield benefits or disbenefits since it could result in either a decrease or increase in air pollution. Air pollutant emissions are estimated based on travel volumes and a per-mile emissions rate. The emissions rate depends on travel speeds, and are estimated in the model based on emission rates generated from the California Air Resources Board (CARB) emissions model, EMFAC.

The value of emissions are based upon those developed in the study by Donald McCubbin and Mark Delucchi, and updated by the GDP deflator to the Year 2000. Emissions vary by the region in which the highway project is being built. Los Angeles values are used for Los Angeles, the national urban area values are used for other urban areas, and the US national average is used for rural parts of California. These values are provided in Table 5-2. Road dust is ignored due to the controversy over the associated health impacts.

**Table 5-2: Health Cost of Motor Vehicle Emissions (\$/ton)**

<b>Pollutant</b>	<b>Rural Area</b>	<b>Urban Area</b>	<b>Los Angeles-South Coast</b>
CO	54	60	115
NO <sub>x</sub>	10,144	13,646	46,615
PM <sub>10</sub>	78,618	110,258	381,859
SO <sub>x</sub>	39,732	55,069	143,469
VOC	749	954	2,898

*In Year 2000 dollars*

The sections that follow describe how emissions are valued for:

- Highway Projects
- Transit Projects.

### **5.5.1 HIGHWAY PROJECTS**

Air pollution emissions for highway projects are calculated given estimates of vehicle travel and speeds. The change in emissions associated with an individual highway improvement depends on changes in VMT and vehicle operating speed along the affected area. In most cases, the affected area is assumed to be the improved segment, but users are able to change this assumption. Benefits are calculated separately for each vehicle type and period and then summed to arrive at total emissions benefits.

The model incorporates separate analyses for peak and non-peak periods because emission rates vary with vehicle speeds, and the relationship is non-linear. A small change in daily average speed (e.g., 28 MPH to 34 MPH) may represent a very significant speed change during the peak period (e.g., 15 MPH to 30 MPH), and a relatively small speed change during the non-peak period. Because the emissions rate for a pollutant like NO<sub>x</sub> is highest at low speeds and at very high speeds, the peak period speed change could result in an overall reduction in the emission rate; calculating effects based on the average daily speed suggests an increase in the emissions rate. Using a single average speed over the course of the day to estimate air pollution effects is misleading.

Cal-B/C accounts for peak-period and non-peak period speeds and travel separately. It also calculates emissions for each period and vehicle class separately and then sums the results. Emissions are calculated based on the following formula:



$$(VMT_{Peak} \times R_{Peak}) + (VMT_{Off} \times R_{Off}) = \text{Total Emissions}$$

where: R = the emissions rate (in grams per mile) and

VMT = vehicle miles of travel

The emissions benefit is calculated by comparing emissions with and without the project for each pollutant and summing:

$$\text{Value of Emissions Benefits} = \text{Value of Emissions}_{\text{Without Project}} - \text{Emissions}_{\text{With Project}} *$$

Separate emission rates were developed for automobiles and trucks using the CARB EMFAC 7 emissions model. The emission rates for automobiles and trucks are based upon composite emission rates across vehicle classes for each EMFAC 7 emission category, for several pollutants: CO, NO<sub>x</sub>, VOC, and PM<sub>10</sub> from vehicle exhaust, and brake and tire wear. The rates represent average emissions per mile, including cold starts. The EMFAC 7 emissions model provides default values for the percent of vehicles in each vehicle category (e.g., light-duty gas vehicles, light-duty diesel vehicles, light-duty gas trucks) for each year of analysis (the fleet mix assumptions change over time). Emission rates are expected to change over time as the vehicle fleet changes. The Caltrans Cal-B/C uses a simplified approach to address emission rate changes: year 2000 EMFAC 7 emissions rates are used for the first ten years of project benefits, and year 2020 emissions rates for the second ten years.

Cal-B/C uses a default value for the percent of commercial trucks on the roadway from EMFAC if the user does not have local information. If the user supplies a local truck percentage, then this percentage is used in place of the default percentage. A future truck mix percentage may also be entered, but the percentage is assumed not to change if no future figure is provided.

The model calculates emissions benefits for each year by looking up emissions on the basis of forecasted speed for that year. Cal-B/C calculates benefits for the entire twenty-year project life-cycle by summing the annual benefits. Vehicle miles traveled (VMT) is calculated as the length of the highway affected by the project multiplied by the total traffic volume for each class.

## 5.5.2 PUBLIC TRANSIT PROJECTS

Investment in transit projects may result in net emission benefits or disbenefits, depending on whether the emissions reduction from new transit riders who shift modes from highway vehicles is sufficient to offset any new emissions generated by the transit project. The reduction in highway emissions is calculated using the methodology for highway projects and considers peak and non-peak emissions separately (based upon

differences in average speeds). Since electric rail transit generates emissions through power-plant emissions, which do not vary by time of day, the model considers peak and non-peak differences only for transit projects involving buses.

Like the highway component of the Cal-B/C, transit emissions include volatile organic compounds including hydrocarbons (VOC/HC), oxides of nitrogen (NO<sub>x</sub>), carbon monoxide (CO), and particulates less than 10 microns in size (PM<sub>10</sub>).

The following gives the formula for the net emissions attributable to a transit project. This formula applies to any year, using appropriately interpolated inputs.

$$\begin{aligned} \text{Net Transit Project Emissions} = \\ \{ \text{Change in Highway Emissions} + - \\ \text{Change in Transit Project Emissions} \} \end{aligned}$$

The same values per ton for each pollutant are applied as in the highway project case.

The expected emission reduction benefits from removing vehicles from the roadway is calculated by the highway component of the model.<sup>26</sup>

For transit projects in areas with no existing transit service, the “without project” emissions estimate is zero, and the change in emissions is just equal to the new project’s emissions. In the case of a transit improvement project, it is necessary to examine the emission levels with and without the improvement project in order to assess the incremental emissions associated with the improvement. The calculations vary with the emission characteristics and rates for different transit modes.

#### 5.5.2.1 Passenger Rail Emissions Rates

For passenger rail, such as commuter rail or other diesel-electric locomotive powered train service, Cal-B/C uses the emission rates given in Table 5-3. These rates were derived from locomotive emissions per brake horsepower hour, horsepower ratings, load factors, and average speeds using CARB estimates. These rates are expressed in tons per train-mile assuming a single locomotive train set, and can be converted to tons per vehicle-mile if divided by the number of vehicles or cars per train.

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<sup>26</sup> The highway component of Cal-B/C does not consider the potential that removed highway trips will be replaced with latent demand in situations where the highway is at capacity.

**Table 5-3  
Passenger Train Emission Rates in Tons per Train-Mile**

<b>Category</b>	<b>2002</b>	<b>2012 &amp; beyond</b>
VOC/HC	19.73	19.73
CO	45.67	45.67
NO <sub>x</sub>	583.58	250.11
PM <sub>10</sub>	62.02	31.01

Source: California Air Resources Board, *1991 Locomotive Emissions Study*

The rates in the first column of the table are used to calculate emissions for the first ten years of the project life-cycle. The rates in the second column are used for the second ten years.

#### 5.5.2.2 Light Rail Emissions Rates

Light rail transit (LRT) systems are assumed to operate on electric power generated from a remote source. As such, there are no exhaust or evaporative emissions directly emitted by the trains. Rather, one must capture the contribution to environmental effects of the power plants that generate electricity, in terms of their emissions. Power plant emissions have been converted to emissions per LRT vehicle-mile, based upon LRT traction power, energy consumption, the mix of power generation methods in California, and their respective emissions per mega-watt hour. This methodology is based on work completed by the California Air Resources Board, the California Energy Commission, and the South Coast Air Quality Management District. These emission rates are given in Table 5-4 for the four types of emissions.<sup>27</sup> Note that rates are expressed in tons per vehicle-mile as opposed to train-mile. If the number of vehicles per train is unknown, then an average of three (3) vehicles is assumed.

<sup>27</sup> Data for CO is not available. Cal-B/C uses an emissions rate for CO based upon the emissions ratio of VOC to CO for passenger trains.

**Table 5-4  
Light Rail Transit Emission Rates in Tons per Vehicle-Mile**

<b>Category</b>	<b>2002</b>	<b>2012 &amp; beyond</b>
VOC/HC	0.06	0.06
CO	0.14*	0.14*
NO <sub>x</sub>	1.13	1.14
PM <sub>10</sub>	0.17	0.17

Source: California Air Resources Board

\* Estimated using VOC/CO ratio for passenger trains.

As with passenger rail projects, the first column of rates is used for the first ten years of a project's life and the second column is used for the second ten years.

#### 5.5.2.3 Bus Emissions Rates

Buses generally travel on roadways with other vehicles, and their average speeds reflect those of the surrounding traffic. In most cases, Cal-B/C assumes that the bus speed is the same as that of prevailing traffic, to take into account congestion effects. However, if a particular bus project has dedicated lanes or facilities, the model calculates emissions based upon the speed of that facility. Like other highway vehicles, emissions for buses are calculated using EMFAC 7 emissions rates for 2000 and 2020.

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## **6.0 NETWORK EFFECTS**

### **6.1 INTRODUCTION**

The impacts of transportation improvement projects are far-reaching, extending well past the immediate project area. For example, the addition of a new highway lane and its resulting mobility improvements may cause traffic to shift from one set of highways to another, or it may result in improved express bus service along this route. Intersection projects impact both the mainline and the intersection route. The benefits of passing lane projects are frequently felt two or three miles downstream from where the construction ended. The impacts felt throughout the transportation network, due to the execution of specific transportation improvement investments, are referred to as network effects.

Benefit-cost analysis frequently provides a quantitative basis for comparing and prioritizing alternative projects. Effective benefit-cost models should be flexible enough to address various project types and their network effects, but should also be simple and easy to use. These requirements present a trade-off between a benefit-cost model's accuracy and its simplicity.

Benefit-cost models tend to address this problem by taking one of three approaches:

- Route-Based Approach - Ignore the benefits beyond the immediate project area
- Extended Corridor Approach - Use standard assumptions to approximate the impacts beyond the immediate project area
- Network-Based Approach - Estimate project benefits based upon the output of a regional planning mode.

The route-based approach represents a "hear-no-evil, see-no-evil" tactic. Benefit-cost models taking this approach fail to capture significant project benefits.

A network-based approach tries to rectify these shortcomings but requires the input of regional planning models and occasionally micro-simulation models (e.g., for passing lane projects).

Some Caltrans districts have regional planning models and micro-simulation models available, while others do not. Districts with sophisticated models can capture benefits, such as network and multi-modal effects that other districts cannot. Although it may seem fair to try to capture all the benefits generated by transportation projects, allowing one set of districts to include benefits that others cannot would place some projects on an unequal footing statewide.

While an extended corridor approach does not include many benefits, it does take into account more benefits than a route-based approach. An extended corridor approach may represent a middle ground.

The sections that follow frame the issues surrounding network and route-based evaluation techniques. Particular attention is paid to passing lanes, which by their nature influence traffic conditions on more than one direction (i.e., roads without passing lanes have higher accident rates as vehicles must cross the median in order to pass). The discussion is organized in the following sections:

- Issues Concerning Networks versus Routes
- Methodologies In Use
- Interchange Project Issues
- Caltrans Methodology.

## **6.2 ISSUES CONCERNING NETWORKS VERSUS ROUTES**

This section examines the differences between benefit-cost models that focus entirely on routes versus models that incorporate network effects. The comparison of network-based versus route-based benefit-cost evaluation suggests several issues:

- Applicability of route versus network-based evaluation techniques for specific project types.
- Model implementation issues including cost, reliability, input data requirements and time.
- Coordination issues including the impact of Caltrans' projects on the facilities of other municipalities and agencies.
- Ability to estimate the full range of benefits and costs associated with a project.

These issues are addressed in the sections that follow.

### **6.2.1 NETWORK EFFECTS**

Benefit-cost analysis is often used to compare competing projects or to assess the economic viability of a particular project. Under Senate Bill 45, the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) may need to examine a wide range of prospective projects. These projects could range from a traditional roadway widening and pavement improvement project, to a less traditional project such as a system-wide traveler information system. Many projects, including some Intelligent Transportation Systems (ITS), are not associated with specific routes. For example, a region-wide traveler information system relies on closed circuit television (CCTV), variable message signs (VMS), and vehicle detection and monitoring systems to help travelers choose alternate routes.

Projects that improve specific routes can lead to:

- Unused capacity on other segments, as traffic shifts to the improved segment
- Increased congestion on access roads, which may offset, to a degree, the capacity increase on the improved segment
- Longer trips, as travelers take advantage of higher speeds on the improved segment
- Shorter trips, as travelers who previously avoided the improved segment begin to use it.

These factors and the potential for induced travel influence the net impact on travel time, speed, and emissions. A route-specific evaluation does not take into account these impacts and neglects a large portion of the benefits or costs associated with transportation improvement projects.

However, under some circumstances, it may be perfectly sensible to assume that the off-route effects net to zero. For example, alignment improvements or resurfacing projects tend to have few impacts outside the specific route. The characteristics of the surrounding transportation system can also play a key role. In a rural area with a limited network, there are few alternate paths to a given facility, so off-route effects are unlikely. In these cases, a network-based approach is not necessary and a route-specific methodology can be accurate. These distinctions suggest the appropriateness of a decision tree for chosen modeling approaches based upon particular project categories.



## **6.2.2 DECISION TREE**

A set of decision criteria was used to determine whether projects required a network-based model or a route-specific model. These criteria are listed below. The characteristics of candidates for which route-specific analysis is appropriate are identified first, followed by the characteristics of candidates for which network analysis is appropriate. Examples of appropriate project types and area/facility characteristics are provided for both categories.

Projects that are well suited to a route-specific benefit-cost evaluation include:

- Resurfacing projects
- Safety improvement projects (e.g., geometric improvements)
- Minor capacity improvement projects (e.g., auxiliary lanes)
- Addition of truck climbing/passing lanes
- Roadway alignment improvements.

Area or facility type characteristics that are well suited to a route-specific benefit-cost evaluation include:

- Rural areas with relatively sparse roadway networks
- Facilities that have no feasible alternate routes (e.g., some bridges or tunnels)
- Transportation systems experiencing relatively low volumes (i.e., facilities are well under capacity).

Types of projects that are well suited to a network-based benefit-cost analysis include:

- ITS projects (e.g., ramp metering, traffic surveillance, driver information systems)
- Most HOV projects (e.g., HOV lanes that are continuous throughout a region or tie into a regional system, freeway to freeway HOV connectors, arterial HOV applications, HOV direct access ramps, etc.)
- Interchange additions or improvements
- Significant capacity improvement projects (e.g., a new road)

- Signal re-timing projects
- New or improved park-and-ride lots.

Area or facility type characteristics that are well suited to a network-based benefit-cost analysis include:

- Relatively dense roadway networks which provide alternate path choices and/or have multiple intersecting facilities
- Transportation systems experiencing relatively high levels of congestion (i.e., some facilities are at or over capacity).

Some of the project and area/facility types mentioned as suitable for network-based analysis are also candidates for an expanded corridor approach that incorporates effects on a limited number of parallel and intersecting facilities.

### **6.2.3 IMPLEMENTATION**

The ease or difficulty in implementing benefit-cost models is a key issue related to adopting route versus network-based benefit-cost evaluation. Network evaluations generally require more time and data, necessitate the use of travel demand forecasting models, and are more costly than route-specific analyses. Network-based benefit-cost evaluations also require more assumptions than do route-specific models (especially network models that have the capability to estimate benefits associated with ITS projects, such as ramp metering).

Although there are a number of different travel demand forecasting models (e.g., EMME/2, Tranplan, MINUTP, T-Model), all lead to common data structures. An important output of these models is trip tables, which are always presented in a zone-to-zone matrix format. One of the network-based benefit-cost models, STEAM, uses the standard trip table output available from travel forecasting models as a critical input to the calculation of benefits and costs.

Traditional four-step travel demand forecasting models are the most appropriate tools available for determining the network impacts of roadway improvements. The areas that require network assessments are those most likely to already have, or soon have, a regional or area-wide travel demand forecasting model. However, since four-step models tend to be developed by Metropolitan Planning Organizations (MPOs) rather

than Caltrans, the need for four-step models could also make Caltrans reliant on data from outside agencies.

Four-step models have their own drawbacks. The models tend to be data intensive, difficult to use, costly to maintain, and tend to cope poorly with induced travel. Even if such a model exists for a particular area, it may not be coded to a level of detail necessary for the analysis of a particular project. Additional refinement may be required to make the model functional and/or applicable for the evaluation period.

Although the use of travel demand forecasting models is a natural step once it is determined that a network-based approach is appropriate, other approaches are available. Less data-intensive approaches that limit network modeling can be used to determine the distributed impacts of roadway projects. Spreadsheet models can estimate limited impacts for specific project types on a relatively simple network, or along an expanded corridor.

## **6.3 METHODOLOGIES IN USE**

Benefit-cost models take a variety of approaches to access the network impacts of projects. The HERS and STEAM, models represent the extremes, while the approach taken by the State of Washington, is of an intermediate level that handles interchanges, but not network effects.

### **6.3.1 HIGHWAY ECONOMIC REQUIREMENTS SYSTEMS (HERS)**

The HERS model can be used, on a national level, to estimate benefits associated with highway investments. The model focuses on highway improvements and analyzes only three types of improvement categories: pavement improvement, roadway widening and roadway alignment improvements. HERS data inputs include average annual daily traffic (AADT), design speed, peak capacity, and other roadway characteristics. HERS only allows the examination of individual highway sections, independently of each other. The model does not address the impacts of highway projects on the surrounding roadway network.

### **6.3.2 WASHINGTON STATE DEPARTMENT OF TRANSPORTATION (WSDOT)**

The WSDOT method is not network-based. Calculations used to quantify the travel time savings and other benefits are based upon an evaluation of the impacts of the proposed project on the mainline. With the exception of one procedure, the WSDOT model is only concerned with the benefits on the specific roadway being improved. The exception is the procedure used to evaluate interchange improvements. This procedure is described later in this paper.

### **6.3.3 SURFACE TRANSPORTATION EFFICIENCY ANALYSIS MODEL (STEAM)**

STEAM provides an example of a network-based, benefit-cost model that takes into account the impacts of projects on the surrounding roadway system. The STEAM modeling framework uses output from standard travel demand forecasting models. Typical inputs into travel demand forecasting models include:

- Population and employment by zone
- Features of the roadway network, such as link distances, speed, and capacity
- Available modes.

Travel demand model outputs that STEAM uses as essential inputs include modal trip tables, which indicate the distribution of trips between specified zones in the network. Highway link speeds and zone to zone travel times are also used as input data to the STEAM model. The model calculates user and non-user benefits including travel time savings, vehicle operating cost savings, accident reduction, vehicle emissions, energy use, noise, etc., based on model inputs and key parametric assumptions.

### **6.4 INTERCHANGE PROJECT ISSUES**

Interchange projects pose a special set of issues for benefit-cost evaluation. Although interchanges are associated with specific routes, these projects may provide benefits to traffic not on the mainline of the route (e.g. the intersecting route). In fact, in some cases, an interchange improvement may negatively impact traffic on the mainline. For example, a new interchange can increase delay on the mainline because of additional merges, diverges, or weaving movements. However, because a new interchange also provides a new access point to a limited access facility, those using it will be less likely to travel on arterials, and will experience lower overall travel times. The primary benefit of a new interchange is due to improved access from local arterials rather than improvements experienced by “through” traffic on the mainline.

Interchange improvements also include upgrades from at-grade intersections to grade-separated interchanges. This type of improvement is likely to provide benefits to both the mainline and cross-street traffic in terms of both travel time and safety.

Interchange improvements may require special treatment for assessment of accident benefits/impacts. For example, improving an at-grade intersection to an interchange can result in a reduction in accidents but may not alter vehicle miles traveled (VMT).

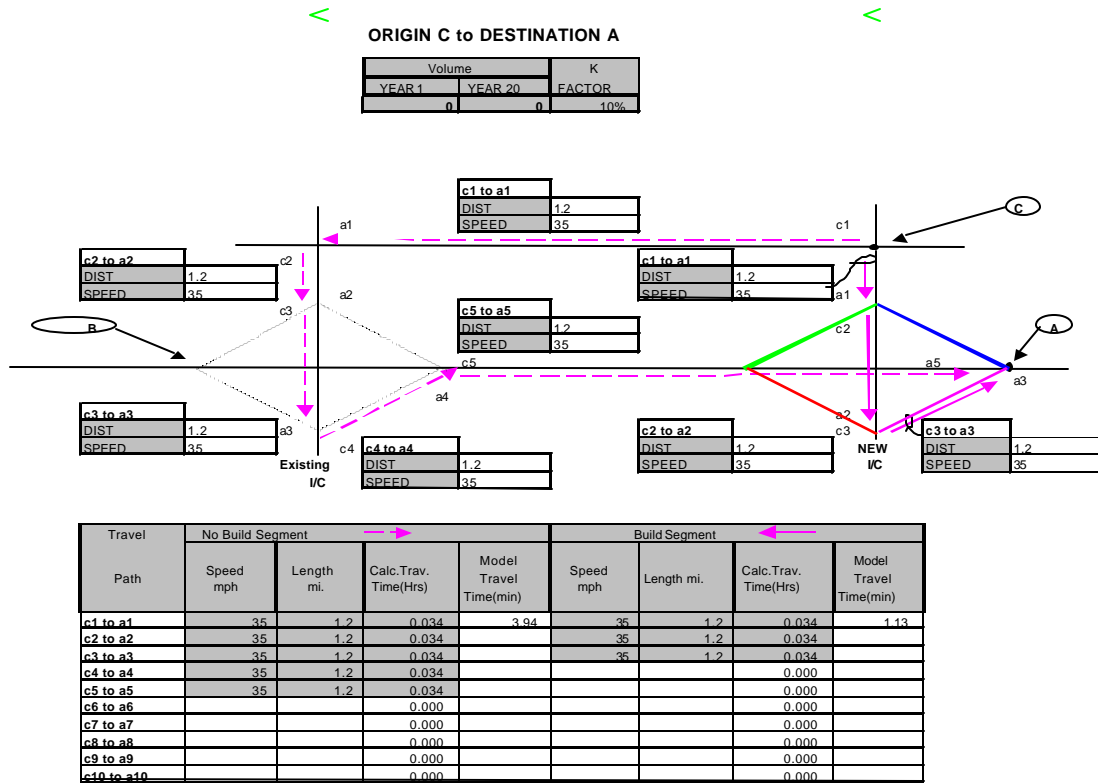
The WSDOT model contains a separate module that analyzes interchange projects. WSDOT categorizes interchange projects into one of several types before conducting the benefit-cost analysis. The agency recognizes that no one standard method can be used for all types of interchanges, but they have prepared a set of standard guidelines.

The guidelines cover the following types of interchange projects:

- Existing at-grade intersection
- Existing at-grade intersection with restrictions (e.g., certain movements restricted by a median barrier)
- New interchange (i.e., no previous connection).

The benefit calculations stem from travel time savings associated with the following: reduction in intersection delay for existing at-grade intersections, delay associated with blocked movements for existing restricted at-grade intersections and new interchanges, and travel time savings associated with better access to a limited-access facility. The level of detail used in the analysis is left to the analyst. To facilitate the process, WSDOT has developed a set of worksheets that help the analyst calculate travel time savings associated with several different types of interchange projects. Figure 6-1 illustrates the complexity of this approach.

**Figure 6-1**  
**Sample WSDOT Spreadsheet Tool to Evaluate New Interchange**  
**at New Access Point**



## 6.5 CALTRANS METHODOLOGY

The Cal-B/C handles the problem of network effects by taking an extended corridor approach. For most projects, the model assumes that users enter highway traffic and transit data for the entire area affected by the project. The model helps users determine the proper impact area for three types of projects:

- Interchange projects
- Bypass projects
- Passing lane projects.

For interchange projects, the model prompts users to input data for traffic on the mainline and on the intersecting roadway. In this manner, appropriate volumes and speeds are used for each roadway effected by the project. The model assumes that other streets and roads are not affected, since information on these facilities are frequently not available to Caltrans and the effects are expected to be minor relative to the mainline and intersecting road.

Cal-B/C uses a similar approach for modeling bypass projects. Bypass projects require effects to be considered on both the existing highway and the bypass. Cal-B/C prompts the user to enter traffic data with and without the project for the existing highway. The model calculates traffic volumes for the bypass by assuming that traffic not using the existing roadway in the with project case uses the bypass. The user must enter the number of lanes separately for the bypass so that benefits are calculated properly.

For passing lane projects, the model adjusts the impact area to account for the tendency of benefits to extend downstream of the project. This methodology is described further in a separate description of the passing lane methodology.

For most projects, the model assumes that the impact area is equal to the highway segment length. Users can adjust the impact area (called “Affected Area” in the model), if they expect it to differ from the segment length. Projects that meet the criteria for a network-based model (described in Section 2.2) are candidates for adjusting the affected area.

Cal-B/C is capable of accepting inputs from regional planning models. The model estimates separate highway speeds and volumes for Year 1 and Year 20, as defined by:

- With project versus without project
- Peak period versus non-peak period
- Trucks versus HOVs versus non-HOVs.

The results of these calculations are displayed and users can change the values. If users have regional planning models that generate speed and volume data specific to the project, this information can be inputted in this screen, replacing the values calculated by the model. Information on transit from regional planning models can be inputted directly into the model. In this manner, Cal-B/C can take a network-based approach if the required inputs are available.



## 7.0 PEAK PERIOD EFFECTS

### 7.1 INTRODUCTION

In a benefit-cost framework, the benefits of transportation investments for highway vehicles are modeled as functions of traffic volume and vehicle operating speed. Caltrans and other agencies collect significant data on traffic volumes as part of the Federal Highway Performance Monitoring System (HPMS) and through other programs. Less information is collected on vehicle operating speed. Frequently, speeds are estimated from traffic volumes using standard formulas and relationships, but methodologies may vary by district or agency. Another challenge is determining which volume and speed data to use- a decision complicated by the fact that the relationships between these variables and project benefits are non-linear.

Daily averages of speed and volume data do not adequately measure the benefits of transportation projects. For example, the highest vehicle emissions occur at very low (congested) and very high (free-flow) speeds. Speeds can vary throughout the day, but most vehicles are likely to travel at either free-flow or congested speeds. Few, if any, vehicles actually travel at the average speed. Since the average speed is somewhere between free-flow and congested speeds, the lowest vehicle emissions occur at the average speed. Estimating emissions using average daily speeds and volumes result in lower estimates than does estimating emissions for congestion and free-flow conditions separately and summing the results.

Benefit-cost models need peak and non-peak<sup>28</sup> data to estimate the benefits of transportation. The most congested period of the day is often called the peak period. While this period frequently occurs during normal commute hours, congested conditions may exist during other times. The actual hours or days during which recurring congestion occurs varies by facility, so the peak period should refer to the period of congestion (morning, afternoon, or other times) rather than typical commute times alone.

If speed data are calculated from traffic volumes and roadway characteristics, rather than measured directly, they must be calculated separately for the peak period and the non-peak period. The relationships between volumes and speed capture the effect of congestion. Estimating a daily speed from average daily traffic (ADT) assumes that traffic levels are even throughout the day. It is more realistic to assume that traffic volumes are higher during the peak period and, hence, speeds are lower. When speeds

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<sup>28</sup> Frequently called off-peak

are estimated from volumes and roadway characteristics, they should be estimated separately for the peak and non-peak period.

The next sections examine the following issues as they concern peak period effects in benefit-cost analysis:

- Issues Affecting Peak Period Estimates
- Theoretical Background
- Methodologies In Use
- Caltrans Methodology.

## **7.2 ISSUES AFFECTING PEAK PERIOD ESTIMATES**

The primary issue related to the use of traffic volumes and speeds in a benefit-cost context is differentiating between peak and non-peak periods during the day. If both are aggregated and represented by ADT and average daily speeds, the impacts on those individuals who travel during peak periods are underestimated. Stated differently, the issue of differentiating between congested and non-congested periods can be summarized as follows:

- Modeling benefits and costs based on ADT and average daily speed does not adequately capture nonlinear effects. For example, the highest vehicle emissions occur at slow speeds (due to stop and go conditions) and very high (free-flow) speeds. Basing emission costs on an average daily volume and speed misrepresents actual impacts because very few vehicles are actually traveling at the average speed.
- The hours and days during which peak and non-peak periods occur vary considerably from facility to facility, and between area types (e.g., rural versus urban). A methodology is required for capturing effects for peak and non-peak periods for these different types of facilities and areas. This analysis must capture effects for the facility in existing and future configurations for both the base and forecast years.
- Although many benefits may be best captured through an analysis that separates peak and non-peak periods, others may be captured just as comprehensively through a daily analysis. Since daily analyses typically require less data input than do peak/non-peak analyses, they are quicker and less expensive to conduct.

The availability of defensible data to differentiate between peak and non-peak periods complicates matters further. For current data, Caltrans must rely on existing sources, generally used in the development of Project Study Reports (PSRs). For future data, Caltrans must rely on regional models (where available). The two data sources need to define the peak period similarly or adjustment factors must be developed to ensure consistency. For example, adjustment factors are needed in the case that a given PSR focuses on peak hour traffic and speeds for a single peak hour, and regional models focus on a 3-hour peak period.

The reasonableness of data is also an issue. Some regional models project demand figures that far exceed the capability of the existing or future infrastructure. Volume-to-capacity ratios of two or higher are not physically possible. Such demand generally leads to expansion of the peak period, a diversion of traffic to alternative routes/modes, or a reduction in overall demand. This issue is generally more important for benefit-cost models that differentiate between peak and non-peak periods.

### **7.3 THEORETICAL BACKGROUND**

Benefit-cost models must account for benefits during both peak and non-peak periods if all benefits are to be considered. The following sections address the parameters necessary to ensure that all benefits are considered. The issues covered include:

- Duration of Congested Period
- Conversion Factors
- Speed Estimates.

#### **7.3.1 DURATION OF CONGESTED PERIOD**

If benefit-cost models are to include peak period analyses in the estimation of project benefits, model users need a methodology for estimating the duration of the congested period for each facility. The congested period is relative to the location and type of facility and can vary by urban versus rural conditions. Although urban freeways typically experience peak traffic on weekdays from about 4:00 AM to 7:00 PM, recreational routes can experience the highest traffic on weekends.

Capacity assessments and other traffic analyses usually ignore the length of the peak period. These analyses focus instead on the peak hour because that hour has the highest capacity requirements and is critical for operations. The time of the peak hour may vary from day to day or from season to season.

The peak hour could be represented in terms of the X<sup>th</sup> highest hourly volume taken during the year, regardless of hour or day. Highway designs are typically based upon the 30<sup>th</sup> or 50<sup>th</sup> highest hour (the design hour volume). However, the design hour volume is higher than a typical peak hour volume.

### **7.3.2 CONVERSION FACTORS**

Traffic volumes are necessary for the peak period and the non-peak period, if benefits are to be valued for both periods. Peak period volumes can be measured directly or estimated by the design hour volume. Non-peak period volumes can be estimated by the portion of daily traffic not captured during the peak period. Regardless of the method chosen, two measures are required.

Some transportation agencies collect both peak hour and daily traffic volumes, while other agencies collect only one or the other. Caltrans publishes peak hour traffic volumes and daily traffic volumes, but in some cases, only one measure may be available. For instance, traffic volumes for some projects may come from local agencies that collect only daily traffic volumes. Model users may need to convert between daily or peak hour data and peak period data.

### **HIGHWAY CAPACITY MANUAL**

The *Highway Capacity Manual* (HCM) provides factors to convert between annual average daily traffic (AADT) and peak hour traffic. However, the HCM presents ranges in terms of the highest hourly volumes throughout the year (from the first highest hour to the 1,000<sup>th</sup> highest hour) that are experienced on different types of facilities. Recreational routes often show wide variations in peak hour volumes. It is not unusual for recreational facilities to have proportions of daily traffic experienced in particular hours to range from 30 percent for the highest hour of the year to 8.3 percent for the 1,000<sup>th</sup> highest hour of the year. Rural facilities also show much variation – from 17.9 percent of AADT for the highest hour of the year to 6.9 percent in the 1000<sup>th</sup> highest hour of the year. Urban routes show very little variation in peak-hour traffic. For urban radial and circumferential facilities, the range in percent of AADT during the peak hour covers a narrow band from approximately 11.5 percent for the highest hour to 7 to 8 percent for the 1,000<sup>th</sup> highest hour (Highway Capacity Manual, 1994).

### **WASHINGTON STATE DEPARTMENT OF TRANSPORTATION**

The WSDOT mobility prioritization process requires users to input “working peak hour volumes” (i.e., average traffic volumes during a “typical” peak hour). Working peak hour volumes are lower than design hour volumes, which represent the 30<sup>th</sup> to 50<sup>th</sup> highest hourly volume experienced during the year, but WSDOT provides a methodology for estimating them from either design hour volumes or ADT. Design

hour volumes can be converted into working peak hour volumes by multiplying design hour volumes by the K30 reduction factors presented in Table 7-1. ADT can also be used to estimate working peak hour volumes by multiplying ADT by the average weekday peak hour percent of ADT, which is also presented in Table 7-1.

**Table 7-1  
WSDOT Peak Hour Reduction Factors<sup>29</sup>**

<b>Category</b>	<b>K30 Reduction Factor</b>	<b>Avg. Weekday Peak Hour % ADT</b>
Large urban areas	.90	8.34%
Other urban commuter	.88	9.89%
Combination - commuter and social/recreational	.83	9.12%
Rural	.75	8.98%
Social-recreational	.60	9.04%
Mountain passes	.45	9.35%

However, these figures were estimated using data for highways in Washington State and may not be appropriate for California.

### **STATE OF INDIANA**

Researchers in Indiana developed a procedure to convert daily volume counts into AM and PM peak hour counts for urban freeways, urban arterials, rural interstates, rural arterials, and rural collectors.<sup>30</sup> They developed these factors for use in the Indiana statewide congestion management system (CMS). Factors to convert average daily traffic (ADT) into AM or PM peak volumes were developed using peak hour volume factors (K) and peak hour directional factors (D). These factors are presented in Table 7-2. The conversion formula is as follows:

<sup>29</sup> Source: Washington State Department of Transportation, Mobility Programming Criteria and Evaluation Procedures, Final Report, June 1998, pages 19 and B-5.

<sup>30</sup> Nishantha R Gunawardena, Kumares C. Sinha, and Jon D. Fricker, "Development of Peak-Hour and Peak Directional Factors for Congestion Management Systems," Transportation Research Board, No. 1552, Transportation Research Board, November 1996, pp. 8-18.

$$DPHV = ADT * K * D$$

Where,

- DPHV = Directional Peak Hour Volume
- ADT = Average daily traffic (both directions)
- K = Peak hour volume factor
- D = Peak hour directional factor

The conversion factors were based on traffic counts conducted from 1991 to 1993 on 60 permanent count stations in Indiana. The counts were recorded on an hourly basis throughout the year. Since these counts were specific to Indiana, the conversion factors may not be appropriate for California readings.

**Table 7-2  
Indiana Peak Hour Conversion Factors**

Highway Type	Peak Hour Volume Factor (K)	AM	ADT (K * D)	PM	ADT (K * D)
		Peak Hour Directional Factor (D)		Peak Hour Directional Factor (D)	
Urban Freeway/Interstate	0.070	0.573	0.0401	0.597	0.0490
Urban Arterial	0.074	0.555	0.0411	0.581	0.0465
Rural Interstate	0.075	0.56	0.0420	0.572	0.0486
Rural Arterial	0.075	0.558	0.0419	0.594	0.0487
Rural Collector	0.076	0.578	0.0439	0.62	0.0453

### 7.3.3 SPEED ESTIMATES

Average vehicle operating speeds for benefit-cost models can come from a variety of sources. For example, they may be speed estimates from regional planning models, estimates from speed-flow charts in the *Highway Capacity Manual*, or direct speed measurements. Since travel-time savings are a function of speed, average speeds are important elements in benefit-cost models. Speeds need to be estimated using consistent methodologies if benefit-cost analyses are to be compared across projects.

Several benefit-cost models estimate speeds based on volumes and roadway capacities or use actual average speeds. For example, STEAM allows users to enter actual hourly speeds or of speeds estimated using average daily weekday traffic, free-flow design speed, and the roadway capacity (Cambridge Systematics, 1997). STEAM estimates

traffic volumes during different periods of the day, and then estimates speeds for the peak period, off-peak period, and the entire day.

Calculating speeds for peak periods and non-peak periods using volumes and capacities specific to the two periods resolves the problem of speeds varying over the day. Using calculated speeds rather than user-entered speed estimates ensures that speeds are determined with consistent methodologies. Thus, projects can be compared.

## **7.4 METHODOLOGIES IN USE**

Computerized benefit-cost models can use several different methodologies to handle the problem of congested and non-congested conditions. Four different models illustrate the range of complexity:

- HERS – peak period spreading using volume-to-capacity ratios
- WSDOT – factors to convert daily data to peak period data
- STEAM – hourly distributions of traffic
- StratBENCOST – peak period and daily data with no spread factor.

### **7.4.1 HIGHWAY ECONOMIC REQUIREMENTS SYSTEMS (HERS)**

The Highway Economic Requirements Systems (HERS) model was developed for the Federal Highway Administration (FHWA) to estimate the benefits associated with highway investments on a national level. HERS inputs include average annual daily traffic (AADT), design speed, peak capacity, and other roadway characteristics. From these data, HERS calculates daily average speed.

The United States Department of Transportation (USDOT) Volpe Center is currently working on methods to incorporate peak/off-peak analyses into HERS. The new methodology uses look-up tables, based on speed-volume relationships developed by a consultant, to estimate the percent of traffic occurring in peak and off-peak periods. The look-up tables contain scaling factors that transform annual average VMT into peak and off-peak VMT. The factors are a function of the AADT/capacity ratio and the functional class of the segment.

The principle that underlies the Volpe update is that congestion spreads beyond peak periods as the AADT/capacity ratio increases. In the Volpe methodology, the peak period is defined as lasting from 6 AM to 9 AM and from 3 PM to 6 PM.

A similar set of factors decomposes average speed into peak and off-peak speeds.

## **7.4.2 WASHINGTON STATE DEPARTMENT OF TRANSPORTATION**

The Washington State Department of Transportation (WSDOT) Highway Mobility Division uses benefit-cost evaluation as part of its mobility prioritization process. Benefits are modeled using peak hour volumes, but WSDOT has developed conversion factors to derive peak hour volumes from average daily traffic (ADT).

The two sets of conversion factors developed by WSDOT are shown earlier in this paper in Table 7-1. The first conversion factor converts ADT into working peak hour volumes. Working peak hour volume is defined as the average hourly volume during the peak period. The second factor converts design hour volumes into working peak hour volumes. Design hour volume is the X<sup>th</sup> (typically 30<sup>th</sup> or 50<sup>th</sup>) highest hourly traffic volume for the year. The design hour volume is frequently used as the standard for designing new facilities. The model determines average peak hour operating speeds using working peak hour volumes, facility types, and speed-flow curves from the *Traffic Engineering Handbook*.<sup>31</sup> Speed-flow curves show the relationship between traffic volume and operating speed for various facility types. The relationships have been developed empirically using data from many states.

## **7.4.3 SURFACE TRANSPORTATION EFFICIENCY ANALYSIS MODEL (STEAM)**

The STEAM model bases benefit estimates upon average daily weekday traffic. Users can enter measured speeds, or the model can estimate speeds based on average daily weekday volume, free-flow design speed, and capacity for both freeways and arterials. To deal with the congestion problem, STEAM makes separate speed estimates for the peak period (7 AM to 10 AM and 4 PM to 7 PM), the off-peak period, and average weekday periods (Cambridge Systematics, 1997).

The speed estimation model included in STEAM was developed using hour-by-hour simulations of traffic volumes and queuing for facilities with different levels of congestion. The hourly traffic distributions were based on research data.<sup>32</sup> Since the hourly distributions can vary by facility type and traffic levels, separate distributions were developed for freeways and arterials with low, moderate, and high ADT (volume)-to-capacity ratios.

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<sup>31</sup> WSDOT cites figures 16.1, 8, 13, and 14 from the *Traffic Engineering Handbook Second Edition*.

<sup>32</sup> Research documented in report prepared by SAIC and Cambridge Systematics, *Roadway Usage Patterns: Urban Case Studies*; prepared for Volpe, June 9, 1994.



#### **7.4.4 STRATBENCOST**

StratBENCOST (Stratified Benefit Cost Model) supports multi-year planning and budgeting. Projects can be ranked by net present value to facilitate preliminary selection of projects for further study. The model provides default values for a number of variables, so users need to enter only minimal data.

StratBENCOST handles the congestion issue by having users define the congested period. Users must enter percent AADT occurring during the peak period and the number of hours comprising the peak period. The model uses the same inputs for the build case and no-build case in the forecast year and base year. StratBENCOST implicitly assumes that the peak period does not change over time, nor is it effected by proposed transportation projects. Peak period congestion cannot spread to other hours in the StratBENCOST model.

#### **7.5 CALTRANS METHODOLOGY**

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) takes into account the difference between the peak and non-peak periods by estimating benefits separately. Since for most model users highway volume and speed data are unlikely to be available by time of day, and because methodologies for estimating speeds from volumes may vary by agency and district, Cal-B/C calculates appropriate speed and volume data given a few simple inputs. The resulting data are displayed to the user and the user is able to change the calculated values, if project-specific data are available.

The model calculates separate speeds and volumes for:

- With project and without project scenarios
- Peak and non-peak period
- Trucks, High Occupancy Vehicles (HOVs), and non-HOVs.
- Year 1 and Year 20.

Values for intervening years are calculated using straight-line interpolation.

The model separates average daily traffic (ADT) data for Year 1 into peak and non-peak period volumes (total period, not average) using an estimate of the peak period duration and the percent of daily traffic occurring during a typical peak hour. On the basis of travel data from the 1991 Statewide Travel Survey, the five highest hourly

traffic volumes occur from 7 AM to 9 AM and 3 PM to 6 PM statewide and these patterns do not vary significantly by region. Each of these hours carries on average 7.8 percent of total daily traffic. Users input the length of the peak period (in hours) into the model and the model estimates the peak period volume using the following formula:

$$\text{Volume}_{\text{Peak}} = \text{ADT} * 7.8\% * \text{Peak Period Duration}$$

The non-peak period volume is calculated as:

$$\text{Volume}_{\text{Non-Peak}} = \text{ADT} - \text{Volume}_{\text{Peak}}$$

These volumes are split into HOV, non-HOV, and truck volumes using percentages supplied by the user. If the user does not have an estimate of percent trucks, the default value is 9 percent, which was calculated from the 1998 California Motor Vehicle Stock, Travel and Fuel Forecast.<sup>33</sup>

Speeds are estimated for the user from the volumes to ensure that speeds are estimated consistently across projects. The model calculates speeds using the standard capacity constraint function found in regional demand models. This function is calibrated to the speed-volume curves found in the 1997 Highway Capacity Manual:

$$\text{Speed} = \text{Free-Flow Speed} / (1 + 0.15 * (v/c)^{10}), \text{ where}$$

v = volume  
c = capacity

The model assumes that the capacity per lane is 2000 vehicles per hour (but the user can change this) and calculates capacity, c, as:

$$\text{Capacity} = \text{Duration of Congested Period} * \text{Number of Lanes} * 2000 \text{ vehicles/hour}$$

Regional planning models and traffic forecasts occasionally produce volume-to-capacity ratios (v/c) in excess of 1.4. This occurs because the models and forecasts predict demand, but do not constrain demand to the capacity of the roadway. In practice, highways cannot support v/c ratios at this level. The model constrains v/c ratios, so they do not exceed 1.4 to ensure that input to the model are reasonable and pragmatic. For a highway with a free-flow speed of 65 MPH, the Cal-B/C formula estimates a speed below 10 MPH for a v/c ratio of 1.4. It is reasonable to assume that speeds will not drop even lower, but, just in case, the maximum v/c ratio is a default parameter that can be changed.

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<sup>33</sup> California Department of Transportation, *TSIP, 1998 California Motor Vehicle Stock, Travel and Fuel Forecast, November 1998.*

Cal-B/C implicitly assumes that the peak period spreads once the congested v/c ratio reaches 1.4. Benefits are calculated for the peak period using a v/c ratio of 1.4 if the actual ratio is higher. However, the model assumes that the peak period expands so that all peak traffic can be accommodated by a v/c ratio of 1.4 and applies the resulting speeds to all peak period traffic. Cal-B/C assumes that traffic in the non-peak period will not become congested by the longer peak period and calculates benefits separately.

Since users may want to override estimated speeds in some cases (e.g., for special facility characteristics that are not captured by the speed algorithm), Cal-B/C displays calculated speeds and allows users to override them with their own speed estimates. If a user overrides a calculated speed, the model prompts the user to enter the reason for the change.

To capture peak period travel on transit, the model prompts users to enter the annual number of person trips and the percentage occurring during the peak period. Users also enter transit travel times during the peak and non-peak period.

## 7.6 REFERENCES

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## **8.0 DISCOUNT RATE**

### **8.1 INTRODUCTION**

Benefit-cost analysis is generally used for evaluation of public investment in major infrastructure projects. Such projects frequently involve structures with long physical and economic lives. Heavy costs are incurred up front, while benefits may flow for 30 years, 50 years, or longer. The difficulty in these analyses is making the right trade-off between present costs and future benefits. The discount rate converts future values to present values and allows the trade-off to be made.

The choice of the discount rate is a central decision in benefit-cost analysis. The appropriate discount rate is a choice external to the analysis and, in the end, is a decision that should be made by policy makers. Economists cannot make the decision for the policy makers. They can, however, suggest the approximate bounds on the range of sensible choices and identify the implications of the alternatives.

At the most basic level, the discount-rate question is about the rate at which people value future consumption in terms of consumption given up now. There is no question that people value present consumption more highly than future consumption. The interest that people are paid to induce them to save, that is to refrain from consumption today, usually exceeds the expected inflation rate. They will give up present consumption only if they get an extra premium on future consumption. Beyond inflation, this premium covers the lost opportunity of present consumption (the real interest rate) and the perceived risk of future consumption (the risk factor). Similarly, people are willing to pay interest in order to increase present consumption. In light of these basic economic facts, benefit-cost analysis must discount future benefits (and costs) to some degree.

The next sections examine the following issues as they concern the selection of an appropriate discount rate for benefit-cost analysis:

- Factors Affecting the Discount Rate
- Methodologies In Use
- Caltrans Methodology

## **8.2 FACTORS AFFECTING THE DISCOUNT RATE**

The discount rate has three components: an inflation expectation, the real interest rate, and a risk factor. The inflation rate is not ordinarily used in benefit-cost analysis. The inflation rate is relevant when an analysis is concerned with financial flows. However, the benefits and costs included in benefit-cost analysis, including the Caltrans model, typically are expressed in real terms. Since benefit-cost analysis uses constant dollar values for comparisons, the discount rate need not include inflation.

The real interest rate is the return that private investors (individuals and institutions) require in return for making a long-term, risk-free investment. The yield on 30-year United States Treasury bonds, minus forecasted inflation, is often thought to be a proxy for this rate. However, the private sector must offer investors a higher return than does the United States Treasury, because there is some degree of risk in private-sector investment. This second component is the risk factor.

### **8.2.1 THE RISK FACTOR: INCLUDE IT OR NOT?**

Whether there should be a risk factor in a public-sector discount rate is debated widely. Some theorists argue that public sector investments involve some risk, so a risk factor is appropriate. According to this line of thinking, the discount rate should be the real return on investment in the private sector. The notion here is that there is no inherent reason why public sector organizations should do any better at choosing capital projects than do private firms. Therefore, the risk factor should be the same, and the discount rate should be the real marginal return on capital in the private sector. Before 1993, this view prevailed in the federal Office of Management and Budget (OMB). For several years, OMB had recommended that federal agencies use a rate of ten percent for benefit-cost analysis.

In 1993, OMB changed its recommendation to seven percent, a rate close to the long-term bond rate at the time. In effect, OMB took the view that a much smaller risk premium would suffice. Since the long-term interest rate includes an expectation of inflation, using it for the real rate suggests that the risk premium is approximately equal to inflation.

### **8.2.2 VALUATION OF FUTURE BENEFITS**

There is no definitive, analytical resolution to the issue of whether to include a risk factor – it is a choice for policy makers. Another way to look at the discount-rate problem is to set aside the risk-factor question and simply consider the issue

of how public officials should treat extremely long-term benefits, those more than 30 years into the future.

The effect of a high discount rate is striking at a 30-year time horizon and even more so further into the future. With a ten-percent discount rate, the present value of benefits/costs in 30 years are very small and the present value of benefits/costs in 50 years virtually disappear. Table 8-1 illustrates, lower rates allow future benefits to retain more of their value when expressed in present terms.

**Table 8-1  
Effect of Selected Rates on Future Values**

Value	Rate Recommended by OMB, pre-1993	Rate Recommended by OMB, post-1993
Discount Rate (%)	10.0	7.0
Present Value of \$1.00 at Year 30	0.057	0.131
Present Value of \$1.00 at Year 50	0.0085	0.0339

Lowering the discount rate from 10.0 percent to 7.0 percent increases the present value of benefits/costs 50 years in the future by a factor of four and 30 years into the future by a factor of more than two.

The unresolved policy challenge is that the benefits being valued do not accrue, for the most part, to the people incurring the costs. Should benefit-cost methodology look at benefits from the point of view of the people living or should it include all people, including those yet unborn, who incur few costs but many benefits?

Even if benefit-cost methodology is limited to people currently alive, people place some value on benefits to future generations. Unfortunately, we do not know what that value is. Some people also take satisfaction from public structures that can be expected to endure. For instance, the Romans presumably enjoyed erecting public buildings and infrastructure that have lasted for millennia. If one thinks that these were wise investments from the point of view of the Romans, then a low discount rate should be chosen. The issue of an appropriate discount rate is somewhat philosophical and rests on the concept of stewardship and the nature of a given society.

### 8.2.3 OTHER ISSUES

Some theorists argue that high discount rates are desirable in times of tight budgets to ensure that only the best projects pass the benefit-cost test. The same end is accomplished, in part, by ranking projects and taking only those that the budget can support. The similarity is only partial because different discount rates lead to different rankings, with high rates favoring projects with earlier payouts. The notion may be valid that, when resources are truly scarce, people strongly favor present benefits over future benefits. The counter argument is that we are a wealthy society and should use some of our capital to build for posterity.

Another point of view holds that, for large projects or for entire networks, such as the Interstate system, conventional benefit-cost analysis fails to account for the full economic impacts. For example, a recent FHWA report showed that highway improvements consistently lead to reductions in business costs in addition to transportation costs<sup>34</sup>. Since benefit-cost analysis focuses on users' transportation costs, the analysis cannot capture effects on productivity and national income. A low discount rate may be a proxy to capture some of these spillover effects. Perhaps a better approach is to extend the analysis to include explicit treatment of such secondary benefits.

Some analysts, including those at OMB, have articulated the view that promoters exaggerate the benefits of public-works projects, so a high discount rate is desirable for eliminating marginal projects of doubtful worth. This view is founded on a perception that some project promoters are not entirely honest or rigorous in their analysis of their projects.<sup>35</sup> To the extent that basic project analysis is done honestly and carefully, the above approach should be avoided since it would lead to the rejection of sound projects.

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<sup>34</sup> Nadiri, Ishaq and Mamuneas, Theofanis, *Contribution of Highway Capital to Output and Productivity Growth in the US Economy and Industries*, Federal Highway Administration, U.S. Department of Transportation, August 1998.

<sup>35</sup> For example, Don Pickrell has documented systematically optimistic ridership forecasts in rail transit planning. See Pickrell, Don, "A Desire Named Streetcar," *Journal of the American Planning Association*, Vol. 58, No. 2, Spring 1992, pp. 158-176.



### **8.3 METHODOLOGIES IN USE**

In STEAM, HERS, and StratBENCOST, users can input whatever value believed to be appropriate, but the models give some guidance:

- STEAM provides a default value of 7.0 percent based on the OMB recommendation.
- HERS, when used by FHWA, is usually run with a 7.0 percent rate, based on the OMB recommendation.
- StratBENCOST requires the user to input a discount rate for the analysis. The model documentation includes some discussion of rates from different sources. It notes that the AASHTO Red Book (1977) and a Texas Transportation Institute Technical Memorandum recommend a discount rate of 5 percent for use in highway planning. It also notes that 5 to 7 percent is the range typically used by DOTs and that NCHRP Report 133 suggests a rate of 6 to 10 percent as the opportunity cost of capital for average risk projects.<sup>36</sup>

### **8.4 CALTRANS METHODOLOGY**

There is a wide spectrum of opinions about discount rates. The high end of the sensible range is the real marginal return in the private sector; the low end is somewhere below the real, long-term, risk-free interest rate (approximated by the yield on 30-year Treasury bonds minus a factor for inflation). Unfortunately, no analytical process indicates at which point to choose along this spectrum.

The Caltrans Cal-B/C uses a discount rate of 6.0 percent. This value is in the middle of the range used typically by DOTs. It is in between the rate recommended by AASHTO and the rate recommended by OMB. Since the Cal-B/C discount rate is slightly higher than the real, long-term, risk-free rate, it accounts for the small degree of risk associated with transportation projects.

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<sup>36</sup> *National Cooperative Highway Research Program. Tutorials and Ready Reckoner for StratBENCOST, p. 50.*

## 8.5 REFERENCES

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## 9.0 PASSING/CLIMBING LANES

### 9.1 INTRODUCTION

The primary function of passing lanes and truck climbing lanes is to widen highways for limited distances and to allow drivers to pass slower vehicles. These lanes are often built because they are more cost effective than adding lanes for the full length of the highway. On highways with relatively low traffic volumes, passing and truck climbing lanes can produce benefits similar to those of lane additions, in terms of accident reductions and time savings, but at lower construction costs. Passing and climbing lanes may lead to additional benefits when compared to lane addition projects, such as improved aesthetics and reduced environmental degradation.

The distinction between passing and truck climbing lanes is subtle. Passing lanes are normally built on relatively flat, two-lane highways and allow faster drivers to pass slower vehicles. Truck climbing lanes tend to be built on extended, steep highway sections and allow faster automobile drivers to pass slower trucks and other large vehicles. On two-lane highways, truck climbing lanes look and function like passing lanes. On multiple-lane highways, truck climbing lanes tend to be longer and function more like lane additions. Truck traffic is constrained to the truck climbing lanes in these cases.

In evaluating the cost-effectiveness of building passing and truck climbing lanes, most computerized benefit-cost models treat them as lane addition projects. This treatment is rational for climbing lanes on multiple-lane highways, because, like lane additions, truck climbing lanes add capacity over long distances.<sup>37</sup> However, this treatment may underestimate safety and travel time benefits for passing or climbing lanes on two-lane highways. Passing and climbing lanes on two-lane highways are relatively short, yet their benefits often extend beyond the highway section containing the lanes. Passing and truck climbing lanes permit faster travelers to pass slower vehicles and accelerate to their desired traveling speeds. Travelers continue to enjoy the ensuing time saving benefits until they catch up with slower vehicles downstream.

In the absence of passing and truck climbing lanes, drivers must face on-coming traffic when passing slower vehicles. In some circumstances, highway geometric constraints and infrequent gaps in traffic limit the ability of drivers to pass slower vehicles. Under these conditions, passing maneuvers create safety hazards for traffic traveling in both

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<sup>37</sup> *The only distinction is that truck climbing lanes have lower capacities than typical highway lanes. The Highway Capacity Manual explains how to calculate this capacity.*

directions. Passing on highways without passing lanes can also impact travel times by causing traffic in the opposite direction to slow down. In the case of two-lane highways, passing and climbing lanes improve safety and travel time by providing protected areas for passing.

The next sections examine the following issues as they relate to the estimation of impacts from passing/climbing lanes:

- Factors Affecting Passing/Climbing Lanes
- Methodologies in Use
- Theoretical Research
- Caltrans Methodology.

## **9.2 FACTORS AFFECTING PASSING/CLIMBING LANES**

The analysis of passing/climbing lanes is relevant primarily for two-lane highways. Climbing lanes are sometimes added to extremely steep sections of four-lane highways, but these lanes tend to act more as lane additions. The *Highway Capacity Manual* notes that two-lane highways are unique because “passing demand increases rapidly as traffic volumes increase, while passing capacity, in the opposing lane, declines as volumes increase. . . . Unlike other types of uninterrupted flow facilities, on two-lane highways, normal traffic flow in one direction influences flow in the other direction” (p. 8-2).<sup>38</sup>

The most important factors used in evaluating the need for passing/climbing lanes are (in general order of importance):

- Percentage of trucks/recreational vehicles
- Grade/slope
- Length of grade
- Lane width
- Vehicle speed differentials
- Number of turnouts
- Traffic volume
- Road curvature
- Directional split of traffic<sup>39</sup>
- Number of intersecting roads.

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<sup>38</sup> Unless stated otherwise, this paper refer to passing and climbing lanes as one entity, although there are important distinctions. Climbing lanes refer to lanes that are added in areas of steep, sustained grades in order to separate slow, heavy vehicles (e.g., trucks and recreational vehicles) from regular traffic. Passing lanes refer specifically to lanes that are added intermittently to provide passing opportunities along two-lane roads.

<sup>39</sup> According to the Highway Capacity Manual, the “ideal” directional split for passing lanes is 50/50, but most rural two-lane facilities range from 55/45 to 70/30, and recreational routes may have a directional split of 80/20. Passing opportunities vary according to the directional split.

These factors also influence the benefits that passing/climbing lane projects can produce. Increases in any of the factors (except lane width and turnouts) result in lower levels of service. The effect becomes more pronounced as the value of each factor increases. For example, the greater the percentage of heavy trucks (particularly in the presence of steep or sustained grades), the greater the decrease in level of service. For another example, the more that traffic levels increase, and the more pronounced that road curvatures become, then the greater the decrease in the levels of service will be. Lower service levels are characterized by increases in platooning (i.e., vehicles bunching together), vehicle delays, unsafe passing maneuvers, and accidents. The construction of climbing/passing lanes can help to mitigate these conditions.

The primary benefits resulting from the addition of passing/climbing lanes are reductions in accidents and travel times.<sup>40</sup> Accidents occur on two-lane highways generally as a result of conflicts between vehicles operating at different speeds and passing maneuvers attempted under unsafe conditions. Accident rates are a positive function of grade, length of grade, and percentage of truck traffic (St. John and Harwood, 1991). Generally, delay savings increase with the level of traffic and the percentage of trucks (particularly in the presence of steep and sustained grades). Time and accident savings decrease as the number of safe passing opportunities increase.

Benefits accruing from the addition of passing/climbing lanes are likely to be felt both within the section of roadway containing the new lane and outside the section. In traffic engineering terms, we expect both downstream and upstream effects to result from relieving bottlenecks along the highway.

### **9.3 METHODOLOGIES IN USE**

Most computerized benefit-cost models are limited in their capabilities in handling passing/climbing lanes, because they treat these lanes as lane addition projects. The models generally rely on changes in average speed to capture time savings and changes in accident rates by facility type to capture safety benefits. By relying on changes in average speed along the highway sections, the models ignore the tendency of passing/climbing lanes to improve travel times even after they end. Since the addition of passing/climbing lanes does not change the highway classification, the models generally do not measure improvements in accident rates.

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<sup>40</sup> One might expect a review of the literature to indicate that vehicle operating cost (VOC) savings will result from the addition of passing/climbing lanes, due to an overall increase in vehicle speeds. However, this benefit is not referenced in the literature, nor does the only model that specifically calculates climbing lane benefits include this benefit. (This model, used by the Washington Department of Transportation, is discussed later.) The literature and other models might ignore VOC savings due to the tendency of extra accelerating and decelerating to cancel out the savings due to increased speeds. Another possibility is that the primary benefits of reduced accidents and travel times may significantly outweigh the relatively small benefit accruing from VOC savings.

However, one benefit-cost model contains a module that addresses some of these concerns. The Washington State Department of Transportation (WSDOT) has developed a benefit-cost model that contains a module specifically for climbing lanes (but not passing lanes). The WSDOT model treats passing lanes as highway lane additions.

The next sections describe modeling approaches used in the WSDOT model and two other computerized models.

### **9.3.1 STEAM**

The STEAM model treats passing/climbing lanes as lane addition projects. Since STEAM is a network-based model, it can potentially capture benefits that occur beyond the highway section receiving the passing/climbing lanes. However, STEAM is only able to capture these benefits if the user has an external micro-simulation model that simulates the effects of passing/climbing lanes on traffic flow. STEAM does not account for characteristics specific to passing/climbing lane projects, such as grade or traffic volume in the opposing direction. The model can measure travel time savings to the extent that the effects are measured by changes in average speeds.<sup>41</sup>

STEAM is unable to quantify the benefits due to reductions in accidents. STEAM does not explicitly model how the addition of passing/climbing lanes influences accident rates. The model can capture a change in accident rates only by changing the facility class. Since highway classifications usually do not make distinctions between two-lane facilities with passing lanes and those without passing lanes, STEAM cannot measure accident reductions due to passing/climbing lanes unless the user manually changes the accident rate inputs.

### **9.3.2 STRATBENCOST**

StratBENCOST was the forerunner of STEAM and it models passing/climbing lane projects in roughly the same manner as STEAM. Like STEAM, StratBENCOST ignores accident savings and captures time savings as a function of changes in average speed. Unlike STEAM, StratBENCOST is a segment-based model and incapable of capturing benefits that occur outside of the highway section receiving passing/climbing lanes, regardless of whether the user has a micro-simulation model.

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<sup>41</sup> Information on how STEAM handles passing/climbing lanes was provided by Patrick DeCorla-Souza.

### 9.3.3 WASHINGTON DEPARTMENT OF TRANSPORTATION

WSDOT has developed a benefit-cost model for analyzing projects within the State. The model includes a separate module for assessing climbing lane projects, which WSDOT defines as passing lanes on an extended slope. The climbing lane module assesses benefits as a function of grade and cannot be used to analyze passing lane projects. The WSDOT model treats passing lanes simply as lane additions.

The climbing lane module calculates benefits using inputs for average daily traffic (ADT), peak-hour volume, percentage trucks, grade, and length of grade. This module distinguishes between lane addition and climbing lane projects by taking into consideration grade and the percentage of trucks on the facility.

The WSDOT module includes what may be considered minimal allowance for downstream effects by adding two-tenths of a mile to the calculation of benefits. The extra distance is included as a proxy for the time trucks need to accelerate to standard operating speed, but it is not likely to capture the full extent of downstream benefits. The WSDOT model developers considered downstream effects but were unable to devise an effective method for handling them.

The module developed by WSDOT estimates savings in travel time and accident costs due to climbing lanes. Travel time savings are calculated based on the estimated number of cars that are expected to follow a truck. This number is estimated for each hour, using the following equation which estimates the probability of a vehicle being a car stuck behind a truck:

$$\text{Probability} = (\text{Truck } \%) * (\text{Car } \%) * (\text{Length of Grade/No-build Speed}) / (\text{Length of Grade/Build Speed})$$

This simplifies to:

$$\text{Probability} = (\text{Truck } \%) * (\text{Car } \%) * (\text{Build Speed/No-build Speed})$$

The third entity in the simplified equation, Build Speed/No-build Speed, is a ratio of the car's speed to the truck's speed.<sup>42</sup> The probability is multiplied by the number of cars in each hour period to arrive at an estimate of the number of cars in each period that are following trucks. The time delay calculation also includes travel time estimates for cars not following trucks. Once travel times are estimated for each component (cars following trucks, cars not following trucks, and trucks), the time savings for the build scenario can be calculated and converted to monetary savings.

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<sup>42</sup> The operating speed of the truck is assumed to be the no-build speed and the operating speed of the car is assumed to be the build speed.

While the basis of this methodology seems rational, the equation can produce questionable results. For example, the equation can result in probabilities over 100 percent. Also, the same outcome is produced whether a given percentage is for cars *or* for trucks (i.e., cars = 90% or trucks = 90%).

A separate module calculates accident cost savings using local data and reduction factors taken from the 1978 FHWA *Informational Guide for Highway Safety Improvements*. The same module is used for calculating accident cost savings due to lane addition projects.

## **9.4 THEORETICAL RESEARCH**

A review of benefit-cost models suggests that most models fail to assess the full benefit of passing/climbing lanes by:

- Ignoring downstream effects on travel in both directions
- Basing accident rates on facility classifications only.

The next two sections review the literature on these two issues and develop estimates of effective impact lengths and accident benefits for passing/climbing lanes.

### **9.4.1 DOWNSTREAM EFFECTS**

The potential for significant effects to occur beyond the project boundaries (i.e. upstream or downstream) is a primary reason why passing/climbing lanes should be modeled differently than lane additions. Harwood, Hoban, and Warren (1988) explored the degree to which passing lanes affect traffic beyond where they terminate. Harwood, Hoban, and Warren did not examine climbing lanes, but, presumably, the results would be similar.

Harwood, Hoban, and Warren define the effective length of a passing lane as “the passing lane itself and the downstream section of two-lane highway where platooning is lower than it would have been without the passing lanes.” (p. 29) They tested different effective lengths using the TWOPAS simulation model,<sup>43</sup> incorporating passing lanes of different lengths and varying levels of traffic. Table 9-1 shows their results.

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<sup>43</sup> Developed by the Midwest Research Institute, TWOPAS is a micro-simulation model that simulates traffic in both directions on two-lane highways.



**Table 9-1**  
**Probability of Being Delayed for Different Effective Lengths**

Effective Length (miles)	Length of Passing Lane (miles)						
	0	0.25	0.50	0.75	1.00	1.50	2.00
One-way Flow Rate = 100 vehicles per hour							
<b>3</b>	33	30	20	17	17	17	17
<b>5</b>	33	31	25	22	19	17	17
<b>8</b>	33	32	28	26	24	22	20
One-way Flow Rate = 200 vehicles per hour							
<b>3</b>	50	39	29	25	25	25	25
<b>5</b>	50	44	37	31	29	25	25
<b>8</b>	50	46	42	38	37	33	30
One-way Flow Rate = 400 vehicles per hour							
<b>3</b>	70	67	57	49	43	35	35
<b>5</b>	70	68	62	57	54	49	38
<b>8</b>	70	69	65	62	60	57	50
One-way Flow Rate = 700 vehicles per hour							
<b>3</b>	82	79	69	63	55	45	41
<b>5</b>	82	80	74	71	66	60	52
<b>8</b>	82	81	77	75	72	68	63

Source: Harwood, Hoban, and Warren, 1988.

Table 9-1 shows the probability that a vehicle is delayed behind a slower vehicle, assuming three different values for the effective length of the lane (3, 5, and 8 miles). The probabilities are stratified by four traffic flow rates and seven passing lane lengths. The probability represents an average across all vehicles in the effective length. For example, at a flow rate of 100 vehicles per hour and in the absence of a passing lane, motorists are queued behind another car 33 percent of the time. With the addition of a one-mile passing lane, the probability of delay occurrence decreases to 17 percent, within the first three miles. The effect of passing lanes diminishes as vehicles move downstream (e.g., a higher probability of time delay occurs eight miles from the passing lane than three miles).

Harwood, Hoban, and Warren derived these results by simulating traffic under “non-ideal” terrain conditions, traffic composition and no-passing zones. Because conditions can vary by case, the authors suggest that the table should be used with “a given base

value of percent time delay [the zero passing lane length column], rather than the traffic flow” (pg. 88).

The results of this study suggest that the travel time saving from passing lanes can be realized downstream. These findings also support the assertion that passing/climbing lanes on two-lane highways can very often offer a more cost effective method of adding capacity and relieving bottlenecks than adding a lane along the entire facility.

As Harwood, Hoban, and Warren (1988) stated:

*"short passing lanes are generally more highly utilized and more cost-effective per unit length in improving traffic performance than extended sections of four-lane highway for two reasons. First, the traffic entering the passing lane from a normal two-lane section is more highly platooned, and thus 'primed' to make the most of the extra lane. Second, the benefits of platoon break-up in the passing lane carry over as reduced delay on the downstream two-lane highway, until new platoons form over number of miles." (p. 14)*

#### **9.4.2 ACCIDENT REDUCTIONS**

A variety of studies conducted over the last twenty years have shown that the addition of passing/climbing lanes on highways reduces accident rates. In a review of previous studies that analyzed 35 passing/climbing lane sites with differing terrain, Harwood, Hoban, and Warren (1988) found that the addition of passing/climbing lanes reduced accident rates by an average of 25 percent. They did not find accident rates vary by terrain.

A separate study by Taylor and Jain (1991) analyzed accident data for all two-lane rural highways in Michigan between 1983 and 1987. Their summary of accident rates with and without passing lanes, by accident type and ADT, are shown in Table 9-2.

**Table 9-2**  
**Change in Accident Rates Due to a Passing Lane**

	<b>Fatality Rate</b>	<b>Injury Rate</b>	<b>PDO Rate</b>	<b>Total Rate</b>
<i>ADT &lt; 5000</i>				
Without passing lane	2.4	60.5	236.5	299.4
With passing lane	0.6	42.0	219.1	261.7
<i>5000 &lt; ADT &lt; 10,000</i>				
Without passing lane	2.6	74.5	193.3	270.4
With passing lane	0.5	59.8	186.5	246.8
<i>ADT &gt; 10,000</i>				
Without passing lane	2.5	101.9	222.8	327.2
With passing lane	2.1	58.8	217.8	278.7

*Source: Taylor and Jain, 1991.*

*Note: Rates are per 100 million vehicle miles.*

Overall, fatality accidents were reduced 16 to 80 percent, injury accidents were reduced by 19 to 42 percent, and property damage only (PDO) accidents were reduced by two to seven percent. However, the ADT group for which the greatest reductions occur varies substantially by accident type. For example, the greatest reductions in fatality accidents occurred for the middle ADT group, while the greatest reduction in injury accidents occurred in the lowest ADT group. This finding suggests that there may be other factors (e.g., passing speed, length of time in platoon, number of vehicles in platoon) involved in the changes in accident rates.

## 9.5 CALTRANS METHODOLOGY

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) takes into account the specific benefits of passing/climbing lane projects by:

- Calculating benefits separately for slow vehicles (i.e., trucks and recreational vehicles) and other vehicles
- Adjusting the length of the highway segment affected by the project
- Using a lower average speed in the absence of passing/climbing lanes
- Reducing accident rates in the “with project” scenario.

The effect of passing/climbing lanes is to remove heavy or slow vehicles (e.g., heavy trucks and recreational vehicles) from existing lanes, thereby improving the flow of traffic for the remaining vehicles. With a passing/climbing lane project, average speeds are faster and accident rates are lower because vehicles do not need to pass slow vehicles by moving into the on-coming lane of traffic.

In addition, Cal-B/C captures improvements in vehicle operating costs and emissions attributable to increasing average speeds. Note that although passing lanes may reduce the variability of speeds, since information on speed variability is rarely available for incorporation in the project control reports (PCRs), the Caltrans model accounts for changes in vehicle operating costs and emissions only through changes in average speeds.

The research conducted by Harwood, Hoban, and Warrant suggests that substantial time savings occur downstream of passing/climbing lanes. On the basis of this research, the model calculates a default effective length for passing/climbing lanes by adding three miles to the length of the lane. Three miles was chosen as a default value to represent a typical case since it is the average length at which approximately half of the time savings are lost. This default effective length can be changed by model users if they have available a micro-simulation model, such as TWOPAS, to capture relevant conditions for specific projects.

The model calculates benefits separately for slow vehicles and other vehicles, since passing/climbing lanes benefit these two classes of vehicles differently. Users are asked to input the percentage of trucks to determine what percentage of traffic consists of slow vehicles. If recreational vehicles make up a significant proportion of slow vehicles, recreational vehicles should be included in the slow vehicle percentage. The remaining vehicles are treated as those affected by the slow traffic.

In the “without project” scenario, the presence of slow vehicles reduces overall average speeds. The model asks users to input the average truck speed (including recreational vehicles, if appropriate). Slow vehicles are assumed to travel at this speed. It is expected that the desired speed of delayed vehicles is the free-flow speed for the facility. The percentage of vehicles delayed by slow vehicles depends on the traffic volume, the speed differential, and several other variables. However, the research conducted by Harwood, Hoban, and Warrant suggests that approximately 50 percent of non-slow moving vehicles are delayed in the absence of passing lanes.

The model assumes that the average speed of non-slow vehicles is the midpoint of the truck speed and the speed the model would normally calculate (i.e., free-flow speed adjusted by the volume-to-capacity ratio). Users can change the speeds calculated by the model if micro-simulation models are available. These models generally require significant data on grades and roadway characteristics that are generally not available. For instance, the HERS model contains fairly complicated equations to calculate average effective speeds based on limiting factors, such as pavement condition, road curvature, average grade, and other factors.

In the “with project” scenario, the model assumes that non-slow vehicles are able to reach their desired speed over the effective length of the project, so the average speed for these vehicles is the speed the model would normally calculate (i.e., free-flow speed adjusted by the volume-to-capacity ratio). Slow vehicle (or truck) speeds are not affected by the project and remain the same.

As a result of these calculations, the model has speed and VMT (traffic volume multiplied by affected length), for slow vehicles and other vehicles with and without the project. Effects for slow vehicles and other vehicles are calculated and summed to get total effects with and without the project. All effects are calculated using the standard procedures with the exception of accident rates.

Accident rates are expected to decline with the implementation of passing lanes. For the “without project” scenario, the observed accident rate for the roadway is used. For the “with project” scenario, accident rates are calculated based upon facility classification, and are adjusted using the percent reductions found in the Taylor and Jain (1991).

## 9.6 REFERENCES

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- Transportation Research Board. 1994. *Highway Capacity Manual: Special Report 209*. TRB, National Research Council. Washington, D.C.

## **10.0 HIGH OCCUPANCY VEHICLE (HOV) LANES**

### **10.1 INTRODUCTION**

High occupancy vehicle (HOV) lanes have been constructed since the 1970s to encourage transit usage and the formation of carpools. HOV lanes are like standard highway lanes, but their use is restricted to vehicles with at least two or three occupants, in most cases. The goal of HOV lanes is to reward transit, carpool, and vanpool users by providing faster, more reliable travel through congested highway segments.

HOV lanes can be constructed by converting existing highway lanes or by building new lanes. Since HOV conversions reduce the number of lanes available to non-HOVs, the public often perceives conversion projects as takeaways. As a result, nearly all HOV lanes are built by new construction.

Although HOV projects result in new lanes, the projects cannot be evaluated simply as lane addition projects. Standard lane additions affect traffic equally, but the restrictions imposed on HOV lane usage mean that the impacts of HOV lanes on HOVs and other vehicles are different. For instance, travelers using other lanes do not enjoy the same time savings that accrue to travelers in HOV lanes. Impacts in HOV and non-HOV lanes must be considered separately.

Some project benefits, such as travel time savings, are a function of the number of people affected. HOVs carry more passengers per vehicle than do non-HOVs (i.e., higher vehicle occupancy), so benefits that accrue to HOVs affect more people on a per vehicle basis. Unlike other lane addition projects, HOV lane projects require an analysis of average vehicle occupancy to capture the cost-effectiveness. Since HOV lane restrictions provide an incentive for people to travel in qualifying vehicles, HOV lane projects may increase vehicle occupancy over time. However, forecasting the impact of HOV lanes on HOV and non-HOV trip generation and mode shares is difficult.

The next sections examine the following issues as they concern HOV lanes in benefit-cost analysis:

- Factors Affecting HOV Lane Evaluation
- Methodologies in Use
- Caltrans Methodology.

## **10.2 FACTORS AFFECTING HOV LANE EVALUATION**

This section describes some of the factors that need to be considered when evaluating the cost-effectiveness of HOV lanes.

### **10.2.1 DIFFERENTIATED IMPACTS**

The use of HOV lanes is restricted to vehicles that meet a threshold occupancy. As a result, HOV lane projects do not impact vehicles equally. While HOVs may experience substantial benefits, non-HOVs may experience fewer benefits or even incur disbenefits. For instance, travelers using other lanes do not enjoy the time savings that accrue to HOV lane travelers. However, travelers in other lanes may enjoy some time savings if HOVs switching to HOV lanes free capacity in general purpose lanes. Impacts in HOV lanes and non-HOV lanes must be considered separately.

### **10.2.2 OCCUPANCY REQUIREMENTS**

The use of HOV lanes is affected by their occupancy requirements. Lane usage may be restricted to: cars with two or more occupants, cars with three or more occupants, or transit only. Occupancy requirements determine how many vehicles are benefited by the construction of HOV lanes and the resulting average vehicle occupancy. If the benefits that accrue to HOVs and non-HOVs are to be evaluated separately, data must be separated according to the occupancy requirement for the proposed facility.

Occupancy requirements vary across California. For example, the occupancy requirement for nearly every HOV lane in Southern California is a two-person minimum. However, both the Route 10 El Monte Busway and the Route 91 Toll Road in Orange County require a minimum of three persons.<sup>44</sup> In the Bay Area, HOV occupancy requirements are different in each county.

### **10.2.3 FORECASTED OCCUPANCY REQUIREMENTS**

Over time, occupancy requirements may change according to the demand for HOV lanes. HOV lanes are generally implemented to encourage the use of carpools, vanpools, and transit by providing faster, more reliable travel. If the lanes are successful in encouraging travelers to switch modes, occupancy requirements may need to be adjusted or HOV lanes become victims of their own success. Too much demand for HOV lanes causes the lanes to become congested. The potential that occupancy requirements need to be adjusted should be considered in evaluating future year benefits.

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<sup>44</sup> *California Department of Transportation District 7, 1997 HOV Annual Report – Executive Summary, July 1, 1998.*



The capacity of HOV lanes (i.e., the maximum amount of traffic that can be handled before occupancy requirements need to be adjusted) depends on the design of the facility and the types of vehicles that use the facility. For most HOV facilities, traffic volumes in excess of 1,200 to 1,500 vehicles per hour per lane (vphpl) result in degraded travel time and reliability. However, some HOV lanes have operated successfully with volumes up to 1,800 vphpl.<sup>45</sup> On average, HOV facilities in Los Angeles County carried 1,110 vehicles per hour during peak hours in 1997.<sup>46</sup>

#### **10.2.4 OCCUPANCY IMPACTS**

HOV lane projects can affect average vehicle occupancy (AVO). In the short term, HOV lanes are expected to shift vehicles among traffic lanes. Higher occupancy vehicles switch to HOV lanes, while vehicles that do not meet the occupancy requirements do not. AVO will be above the occupancy threshold on HOV lanes and decline on general purpose lanes. In the longer term, HOV projects may encourage drivers to shift modes from single occupant vehicles to carpools, vanpools or transit. As a result, overall AVO may increase while average daily traffic (ADT) decreases as compared to the no-HOV case.

#### **10.2.5 PEAK PERIOD EFFECTS**

Benefits for HOV lanes, like other highway projects, need to be evaluated for peak and non-peak traffic separately. HOV lanes are generally built to relieve congestion for HOV vehicles. Since the greatest congestion occurs during the peak period, benefits accrue primarily to peak period travelers. Also, many HOV lanes are operated only during the peak period.

HOV lanes can also impact non-peak period travelers. Some non-peak period travelers may want to travel during the peak period, but refrain from doing so due to congestion. If the additional capacity provided by HOV lanes relieves congestion on general purpose lanes during the peak period, some non-peak period travelers may change when they travel. While this shift increases traffic during the peak period, it reduces traffic during the non-peak period. Modeling these shifts requires knowledge of when travelers want to travel. The phenomena has not been researched extensively and is generally ignored by regional planning models.

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<sup>45</sup> *National Cooperative Highway Research Program (NCHRP) HOV Systems Manual, February 1998 Draft, Page 5-43 to 5-44.*

<sup>46</sup> *California Department of Transportation District 7, 1997 HOV Annual Report – Executive Summary, July 1, 1998.*

### **10.2.6 INDUCED TRIPS**

Adding HOV lanes may free capacity in general purpose lanes by causing existing HOVs (and travelers that shift modes) to use the new lanes. If the demand for travel exceeds baseline capacity, the capacity freed by HOV lanes may be replaced by latent demand. Latent demand means that travelers are induced to make trips not previously made. In the case of induced trips and trips that shift from the non-peak period, existing forecasting methods may not adequately capture the benefit that travelers place on being able to travel in the peak versus a less desirable time or not traveling at all.

### **10.2.7 TRAVEL TIMES**

Travel time savings (and reliability) are assumed to encourage travelers to shift from non-HOV travel to HOV modes. However, calculating these benefits based upon changes in average speed may overstate the true time savings by ignoring the door-to-door time costs associated with transferring modes or forming a carpool.

### **10.2.8 OPERATING COSTS**

The effect of HOV lanes on vehicle operating costs is varied. Operating costs are generally a function of average speed, speed variations, vehicle type, and vehicle miles traveled. Operating costs are higher at low and high speeds, and lower at medium speeds. If HOV lanes allow HOVs to travel at higher speeds then they would on congested facilities, HOV lanes may increase operating costs. However, large variations in speed can also lead to higher operating costs. If HOV lanes reduce “stop-and-go” travel for HOVs and stabilize operating speeds, HOVs experience lower operating costs due to lower speed variations. If HOV lanes encourage people to travel by transit or allow travelers to take shorter paths, operating costs may also be reduced.

Assessing these effects in detail requires traffic simulation models, however general assessments can be made based on volume-to-capacity estimates and experience on other roadways with similar characteristics.

### **10.2.9 ACCIDENT COSTS**

Depending on the physical design of HOV lanes (e.g., the presence of barriers, the degree to which access is controlled, switchable versus dedicated lanes), adding HOV lanes can affect highway safety and result in higher or lower accident rates than facilities without HOV lanes. In some cases, traffic conditions are dramatically different in HOV lanes than in other lanes. Drivers may need to accelerate quickly from nearly stopped traffic in general purpose lanes to free-flow speed in HOV lanes. The speed differential between vehicles already in HOV lanes and entering traffic can decrease safety and increase accident costs.

The Federal Transit Administration has found that accident rates are generally lower for barrier-separated HOV lanes than for adjacent mixed flow lanes. HOV lanes that are separated from general purpose lanes using only a painted line tend to have higher accident rates. However, HOV accident rates vary substantially by facility when averaged across all HOV facilities (regardless of type) accident rates are not unlike those for general highway facilities.<sup>47</sup>

Accident costs are a function of the average vehicle occupancy. As vehicle occupancy increases, so does the number of fatalities and injuries per vehicle in fatality and injury accidents. If HOV lanes increase average vehicle occupancy, accident costs increase.

### **10.3 METHODOLOGIES IN USE**

Many computerized benefit-cost models, such as the Highway Economics Requirements System (HERS), treat HOV lane projects as lane additions. The new HOV lanes are expected to have the same capacity as general purpose lanes. Also, average vehicle occupancy, average operating speed, and average daily traffic are forecasted to be the same for HOV projects as they are for other capacity improving projects. Many of the issues discussed earlier hamper the ability of these models to estimate HOV benefits accurately.

Other benefit-cost models explicitly consider the impacts of HOV lanes using a variety of techniques. In the sections that follow, we describe models that use three such techniques:

- Adjusting the average vehicle occupancy (e.g., WSDOT model)
- Using the output of regional travel demand models (e.g., STEAM model)
- Treating HOV lanes as added capacity (e.g., MicroBENCOST model).

A fourth section describes methods for forecasting HOV demand.

#### **10.3.1 WASHINGTON STATE DEPARTMENT OF TRANSPORTATION**

The Washington State Department of Transportation (WSDOT) Highway Mobility Division currently uses benefit-cost evaluation as part of its mobility prioritization process. WSDOT has recognized the need to analyze HOV improvements separately from other improvements and developed a special module to analyze HOV impacts. WSDOT is currently reviewing the methodology and assumptions used in the prioritization process, so the discussion that follows is based upon the existing model.

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<sup>47</sup> Federal Transit Administration, *Characteristics of Urban Transportation Systems*, September 1992.

The prioritization process requires several user inputs for assessing HOV lanes:

- AVO for HOVs
- AVO for other vehicles
- HOV volumes for the base case and for 20 years into the future
- Traffic volumes in general purpose lanes for the base case and for 20 years into the future.

Travel time savings for HOVs and for general purpose traffic are calculated separately. Savings are then converted to dollars and summed. AVO is incorporated into travel time savings by adjusting cost parameters by AVO. For example, if travel costs for non-trucks are \$10.00 per person and the AVO is 1.3, then travel costs for non-trucks are \$13.00 per vehicle. Similarly, if travel costs for HOVs (including buses) are \$10.00 per person and the AVO is 3.7, then travel costs are \$37.00 per vehicle. By considering AVO explicitly, the WSDOT model is able to capture impacts per person.

The WSDOT model treats accident cost and operating costs impacts as it would for lane addition projects.

The model assumes that HOV occupancy requirements change over time as the demand for HOV lanes increase. The occupancy requirement changes from 2+ to 3+ during the first year that the number of 2+ HOVs exceeds 1500 vphpl during the peak hour.

### **10.3.2 SURFACE TRANSPORTATION EFFICIENCY ANALYSIS MODEL (STEAM)**

The Surface Transportation Efficiency Analysis Model (STEAM) uses a network rather than a route approach to estimate cost-effectiveness. The model accepts inputs directly from regional four-step travel demand models. Inputs include person trip tables for passenger travel and vehicle trip tables for truck travel.

STEAM allows users to identify market sectors. Sectors may include different modes of transportation, such as automobiles, trucks, carpools, local buses, express buses, light rail, heavy rail, or other modes. For each market sector, users indicate AVO for the build and no build scenarios. The model uses AVO to estimate the number of vehicle trips for a given market sector based on the person trip tables. STEAM estimates data for single time periods. If users want to conduct life-cycle analyses, separate estimations are required for each time period.

The ability of STEAM to evaluate the impacts of HOV lanes is limited by regional travel demand models. If the regional models used designate HOV lanes as separate links, then the models can generate data specific to HOV lanes, including average speed, traffic volume, and ADT. Users can designate HOVs and other traffic as different market segments and estimate the travel time savings associated with each.

Vehicle operating costs and accident rates can also be estimated for each market segment. Unless users adjust the operating costs and accident rates associated with HOVs, the model does not treat HOV lanes differently from lane additions (except for the difference in ADT estimates).

### **10.3.3 MICROBENCOST**

MicroBENCOST is a planning-level economic analysis tool developed by the Texas Transportation Institute (TTI) under the National Cooperative Highway Research Program Project 7-12. MicroBENCOST is capable of analyzing a wide range of highway improvements, including HOV lanes.<sup>48</sup> The model considers three main benefits that result from transportation improvements: savings in delay, reductions in vehicle operating costs (including fuel consumption), and reductions in accident costs. Benefits and costs are calculated for a 24-hour period over a multi-year timeframe by comparing unimproved and improved conditions.

MicroBENCOST estimates benefits and costs for HOV lanes by treating them as “added capacity” measures rather than lane additions. In contrast to lane addition projects, the model considers the effect on AVO and the lower capacity increase for HOV lanes. Users are asked to provide several inputs:

- Average daily traffic (ADT) for the base year
- Average annual traffic growth rate over a 20-year analysis period
- Composition of automobile fleet, including occupancies
- Composition of truck fleet
- Distribution of ADT by hour for a 24-hour period
- HOV lane average vehicle occupancy
- Percent of people using HOV lane inbound and outbound.

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<sup>48</sup> Daniels, Ginger, “Are HOV Lanes Cost Effective Improvements? An Analysis of the Benefits and Costs of Texas HOV Lanes,” Prepared for the 68<sup>th</sup> Annual Meeting of the Institute of Transportation Engineers, August 1998.

MicroBENCOST is typically used to assess the impact of recently implemented or existing HOV lanes. The model could be used for proposed HOV lanes, but a number of assumptions need to be made regarding the input variables. Also, the program may require some modifications to handle concurrent flow HOV lanes (it has been used primarily for contra-flow and/or reversible lanes).<sup>49</sup>

#### **10.3.4 HOV DEMAND FORECASTS**

A variety of techniques have been used to forecast demand for HOV lanes. The more sophisticated methods rely on forecasts of demographic data to estimate future travel demand using regional travel demand forecasting models. Regional mode choice models are used to develop trip tables showing HOV origins and destinations. The trip tables are assigned to highway networks to produce HOV volume forecasts.

The development of these models is a significant undertaking and requires extensive resources to set up and maintain. While the models may produce reasonable results at the aggregate level (if well calibrated), estimates are often unreliable at the link level and not sensitive to the introduction of individual HOV facilities to the system.

A simpler, and more conservative approach used for estimating future HOV demand is to assume that the future proportion of HOV traffic is the same as that observed in existing traffic. In this case, forecasts of HOV demand are derived from forecasts of general traffic demand. This approach does not account for the potential for the proportion of HOV travel to increase as a result of the introduction of HOV facilities. It also does not account for increasing congestion on the general traffic lanes, which could attract even more trips to the HOV facility. This approach also does not consider the potential for travelers to shift from one HOV mode to another (e.g., from transit to carpools).

Other demand estimation techniques represent a compromise between sophisticated and simplistic methods. These techniques provide the ability to focus on individual facilities and estimate potential mode shift. Frequently, these techniques are referred to as “sketch planning” demand forecasting models.

Two examples of sketch planning models are the Charles River Associates (CRA) model,<sup>50</sup> and “Quick HOV”.<sup>51</sup> Both models are capable of forecasting demand for HOV facilities on freeways or arterials. Data inputs include: the operational and design

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<sup>49</sup> *Personal Communication, Ginger Daniels, Texas Transportation Institute, December 21, 1998.*

<sup>50</sup> *United States Department of Transportation, Federal Highway Administration, Predicting Travel Volumes for HOV Priority Techniques – Users Guide, Prepared by Charles River Associates Incorporated, April, 1982.*

<sup>51</sup> *Dowling Associates, Cambridge Systematics, Systan, Inc. and Adolph D. May, Predicting the Demand for High Occupancy Vehicle Lanes QUICK-HOV Software User Guide and Reference Manual, September, 1996.*

characteristics of the proposed facility, the current number of high occupancy vehicles (HOVs) and non-HOVs using the facility, and the HOV lane occupancy requirement (e.g., 2+, 3+, transit only).

#### **10.4 CALTRANS METHODOLOGY**

The primary difference between an HOV lane project and a conventional lane addition project is that for the peak period, when the HOV lanes are in operation, the highway essentially operates as two parallel highways. One serves HOVs and the other serves non-HOVs. The two “highways” operate at different speeds and volumes as well as different capacities. The HOV lane is usually restricted to vehicles with 2+ or 3+ occupants and the other general purpose lanes carry vehicles that do not meet the HOV restrictions.

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) calculates travel time, vehicle operating costs, accident costs, and emissions costs separately for HOV lanes and general purpose lanes during the peak period. These effects are summed and added to non-peak period effects. The total effects with the project are compared to those without the project to estimate the project benefits.

In order for these calculations to proceed, separate speed, traffic volume, AVO, and capacity estimates are required for HOV lanes and general purpose lanes for the peak period in the current and forecast years. The model allows users to enter simple inputs and then calculates the required data using standard assumptions. If regional planning models are available and able to provide information on HOV lane travel characteristics, users can review volume and speed data calculated by the models and adjust as necessary. However, Cal-B/C is capable of estimating the benefits of HOV lanes in the absence of a regional planning model.

Most of the user inputs for the HOV analysis are similar to those for the standard highway improvement case. Users already input:

- Average daily traffic (ADT)
- Duration of the peak period (in hours)
- Number of general purpose lanes
- Free-flow speed.

In the HOV case, users supplement this information with:

- Average hourly HOV traffic (during a typical peak hour)
- Number of HOV lanes.

The model assumes that the free-flow speeds on the HOV lanes and on the conventional lanes are the same.

Cal-B/C uses the average hourly HOV traffic to separate the peak period traffic into HOV and non-HOV volumes. The number of HOV lanes is used to calculate the capacity of the HOV facility, assuming a per-lane capacity of 1500 vehicles per hour for HOV lanes.

Using the traffic volumes, lane capacities, and free-flow speeds, the model calculates average vehicle speeds in the HOV lanes and general purpose lanes for the peak period. The model assumes that HOV lanes do not affect non-peak period speeds.

The model then calculates accident costs, operating costs, and emission costs following the standard methodology for general highway projects.

Travel time savings are a function of the number of people using the facility and are estimated separately for HOVs and non-HOVs. For each group of vehicles, travel time savings are calculated using the appropriate volume, average vehicle speed, and average vehicle occupancy (AVO) in the peak period. Travel time savings are calculated separately in the non-peak period.

The model allows users to enter “with project” and “without project” AVO figures for:

- General purpose traffic in the peak period
- General purpose traffic in the non-peak period
- HOVs in the peak period.

For general highway projects, the model provides default AVO figures based on the 1991 Statewide Travel Survey. The Statewide Travel Survey indicates that the AVO statewide is 1.44 for the entire day and 1.38 during the morning peak period. On the assumption that the morning peak is representative of all peak periods, the model uses a default value of 1.38 for peak period AVO. The Statewide Travel Survey also indicates that approximately 39 percent of all driver trips occur during the peak period. Since the other 61 percent of driver trips must occur during the non-peak period and



the AVO for the day must be 1.44, the model uses a default value of 1.48 for non-peak period AVO.

For HOV lanes, the model adjusts the default AVO values depending on the HOV lane restrictions. The model assumes that all eligible vehicles use the HOV lanes during the peak period. In the case of an HOV-2 (every HOV must have 2+ occupants), the default AVO on the HOV lanes is 2.05 on the assumption that five percent of HOVs are three-person carpools and the remainder are two-person car pools. In the case of an HOV-3, the AVO default is 3.0 on the assumption that the number of carpools with four or more people is negligible.

Since nearly all HOVs use the HOV lanes, the model assumes that the AVO is 1.0 on conventional lanes in the HOV-2 case. Estimating a default AVO for the HOV-3 case is some what more difficult, since two-person carpools remain in the general purpose lanes. The model assumes a ten-percent reduction in the number of passengers on general purpose lanes, so the default AVO for general purpose lanes is 1.34. These AVO assumptions are summarized in Table 10-1.

**Table 10-1  
Default AVO Values**

<b>HOV Restriction</b>	<b>Peak HOV</b>	<b>Peak Non-HOV</b>	<b>Non-Peak</b>
None	1.38	1.38	1.48
HOV-2	2.05	1.00	1.48
HOV-3	3.00	1.34	1.48

Following these adjustments, the model calculates travel-time savings, accident costs, operating costs, and emission costs using the already established parameters. HOV lanes are assumed not to affect accident costs nor to affect vehicle operating costs, or emissions costs beyond what is captured by changes in average operating speed. The primary difference from the standard highway project is that calculations are separated for HOV lanes and general purpose lanes and the results summed. Benefits are still calculated by comparing the “with project” case to the “without project” case.

Since speeds, volumes, and AVOs are considered separately for HOV and non-HOV lanes, this methodology also allows benefits to be calculated for projects that do not construct HOV lanes, but occur along segments that already have HOV lanes.

The model assumes that all affected traffic is entered by users. If users enter higher traffic volumes in the “with project case” than in the “without project case,” the model assumes that additional traffic is induced travel. By improving the flow of traffic in all lanes, HOV lanes could induce or divert additional non-HOV traffic to take advantage

of the capacity freed by HOVs. The model calculates the associated benefits using a standard economic technique - consumer surplus theory.<sup>52</sup> The user has the option of ignoring the benefits due to induced travel.

This methodology ignores potential complicating situations. HOV lanes could attract existing HOVs from other roads or cause non-HOV travelers on other roads to form carpools and use the HOV lanes. Estimating these effects requires complex analysis and is beyond the scope of the Cal-B/C.

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<sup>52</sup> Under consumer surplus theory, the economic benefit to new travelers is equal to the change in consumer surplus (the area under the demand curve, but above the equilibrium price). Cal-B/C calculates the value of induced demand as 0.5 multiplied by the reduction in travel time and the number of additional travelers. For more information, see the separate description on the methodology for valuing time.

## 10.5 REFERENCES

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