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

Technical Supplement to User's Guide

Volume 2: Transportation Management Systems (TMS), Operational Improvements, Pavement Rehabilitation, and Economic Value Updates

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I. INTRODUCTION

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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. This report provides supplemental technical documentation for recent updates to the base Cal-B/C model that cover transportation management system (TMS)/intelligent transportation system (ITS) investments as well as operational improvements. This new version of Cal-B/C builds on an interim revision, completed in 2000, that allows Cal-B/C to handle pavement rehabilitation projects. In addition, the latest Cal-B/C includes new fuel consumption and emissions tables as well as updated economic values in Year 2003 dollars.

Caltrans used the base version of Cal-B/C to conduct investment analyses of improvement projects proposed for the interregional portion of the State Transportation Improvement Program (STIP). The latest update expands the base model and is part of Caltrans' efforts to mainstream ITS and implement the Transportation Management System (TMS) Master Plan produced by the Caltrans Division of Traffic Operations. It also builds on research into the benefits of ITS sponsored by the Caltrans Division of Research and Innovation and the Federal Highway Administration's ITS Deployment Analysis System (IDAS). As a result of the latest update and the 2000 update, Cal-B/C is able to handle most of the projects included in the State Highway Operation and Protection Program (SHOPP).

This volume explains changes made to Cal-B/C as part of the most recent update. The report presents the technical framework, research, and assumptions used to incorporate TMS and operational improvements. It explains the approach taken to model projects, the method for developing parameters, and limitations of the new model. The report also documents updates made to lookup tables (so they reflect current research) and to economic values (so they are in Year 2003 dollars).

This volume also documents the changes made during the 2000 model revision. It presents the technical framework, research, and assumptions used to incorporate pavement rehabilitation projects. The latest version of Cal-B/C encompasses both updates and includes all of the revisions described in this technical supplement to the user's guide.

Documentation of supplemental updates is provided in the following sections:

- *Overview of Revised Framework* – describes the base Cal-B/C model, design principals for the revised model, and modifications made to update the model. This section also documents the recent updates made

to the lookup tables and economic values (see the Parameters sub-section).

- *Review of IDAS Model* - identifies the inputs and outputs required by IDAS for the evaluation of ITS projects. It also discusses some of the relevant issues for evaluating these improvements within the Cal-B/C update.

- *Transportation Management System (TMS) Projects* - examines on-going research sponsored by Caltrans Research and Innovation into the benefits of ITS projects. It reviews the benefit-cost modeling conducted for the TMS Master Plan, the Caltrans Design Manual, the Federal Highway Administration (FHWA) ITS Benefits and Costs Databases (which are developed and updated in tandem with IDAS), computerized benefit-cost models (such as SCRITS, STEAM, SPASM, IMPACTS, and HERS), the Highway Capacity Manual, and simulation models. This sectional also describes the updated Cal-B/C methodology for TMS projects.

- *Operational Improvements* – discusses relevant issues for evaluating operational improvements and describes the updated Cal-B/C methodology.

- *Pavement Rehabilitation* – outlines the changes made to the Cal-B/C model in 2000 to accommodate roadway rehabilitation projects that improve pavement condition. This section is adapted from earlier documentation and may describe, as background, Caltrans practices that are now out of date.

- *References* – provides a bibliographical listing of sources consulted for the TMS, operational improvement, pavement rehabilitation, and economic value updates.

II. OVERVIEW OF REVISED FRAMEWORK

II.   OVERVIEW OF REVISED FRAMEWORK

1.0   PRIOR MODEL

The base version of Cal-B/C is a Microsoft Excel spreadsheet that provides economic benefit and cost analysis for a range of capacity-expansion transportation projects. The model measures, in real-dollar terms, 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.

Each of these benefits are estimated for a peak (or congested) period and a non-peak (or un-congested period). The distinction is intended to capture the difference in benefits during congested and free-flow conditions on the highway as well as different operating characteristics for transit at peak times of the day. It is understood that some travel demand models have set peak periods that do not necessarily correspond to the congested period on the highway. Cal-B/C can accept these data in lieu of congested period data.

The model consists of ten sheets in an Excel workbook. Users generally refer to only the first four worksheets (including one that provides instructions and reference materials) to conduct analyses. The six remaining worksheets perform calculations or store default data inputs and economic parameters.

The first worksheet in the model provides *Instructions*. The instructions include short descriptions of each step involved in performing a basic analysis and hints on how to avoid potential pitfalls.

The *Project Information* sheet is the main data-entry worksheet. Users enter descriptive information about projects, expected traffic demand, accident rates, transit data (for transit projects only), and expected project construction and operating costs. The sheet also has a button linked to a macro that allows users to run analyses for bypass and interchange projects.

Caltrans provides Districts with "District input sheets" to use for submitting project information to Headquarters. These input sheets look similar (but are not identical) to the Cal-B/C project information sheet. For each project, a District is asked to submit only relevant data using one of several input sheets tailored to a specific type of project.

The *Model Inputs* page in Cal-B/C contains information about the highway speed, volume, and accident data used in the calculation of benefits. This sheet allows users to check the highway data estimated by the model from the project information sheet and override the calculated values with project-specific information, if such information is available. Some users may have volume and speed estimates and projections from regional travel demand forecasting models. Users can use peak and off-peak period volumes and speeds from regional demand models to override the calculated values produced by Cal-B/C. The model calculates speeds using speed/volume relationships found in the 1997 Highway Capacity Manual.

The *Results* sheet presents the final investment measures and itemized first-year benefits. The sheet allows users to include the effects of induced travel and vehicle emissions. Cal-B/C calculates induced travel benefits using consumer surplus theory.

1.1   Inputs

Cal-B/C requires relatively few user inputs. Cells in the spreadsheets are color-coded. Green cells represent required data (i.e., users must input values in order for the model to work). Red cells provide default values, such as average vehicle occupancy, that users can change if needed. Blue cells reflect data items calculated by the model, but can be changed if more detailed data are available. Blue cells contain values that are likely to change from the base case.

The next several bullet points lists the inputs available in Cal-B/C by cell type.

Green Cells

- Type of project
- Project location (urban Southern California, urban Northern California, and rural California)
- Length of construction period
- Highway design
  - Number of general traffic and High Occupancy Vehicle (HOV) lanes
  - Free-flow speed
  - Segment length
- Average daily traffic (ADT) for current and forecast years
- Average hourly HOV traffic (HOV projects only)
- Truck speed (truck lane or passing lane projects only)
- Highway safety data (3-year statistics for facility and statewide average)
  - Fatal accidents
  - Injury accidents
  - Property damage only (PDO) accidents
- Transit data
  - Annual person-trips for base and future years

- – Annual vehicle-miles for base and future years
- – Average vehicles per train (rail projects only)
- – Reduction in transit accidents due to the project (safety projects only)
- – Average travel time on transit (including transfers and wait times)
- Project costs
  - – Support (e.g., engineering design and management costs)
  - – Right-of-way acquisition
  - – Construction
  - – Maintenance and operating
  - – Mitigation
  - – Rehabilitation (e.g., pavement overlay, vehicle, track, or station refurbishment)
  - – Mitigation
  - – Other

Red Cells

- Length of peak period
- Percent trucks (including recreational vehicles)
- Average vehicle occupancy (AVO) for peak, non-peak, and HOV lanes
- Transit data
  - – Percent of person-trips occurring during the peak period
  - – Percent of new person-trips from parallel highway

Blue Cells

- Length of segment affected by project
- ADT for base (project opening) year

If regional demand model (or other detailed) data are available, the following data can be changed on the model inputs sheet:

- Highway inputs for peak and non-peak periods
  - – HOV, non-HOV, and truck volumes
  - – HOV, non-HOV, and truck speeds
- Highway accident rates and adjustment factors (for the existing and new facilities)
  - – Fatal accidents
  - – Injury accidents
  - – PDO accidents.

1.2   Outputs

Cal-B/C summarizes analysis results on a per-project basis using several measures:

- Life-cycle costs (in millions of dollars)
- Life-cycle benefits (in millions of dollars)
- Net present value (in millions of dollars)
- Benefit/cost ratio (benefits divided by costs)
- Rate of return on investment (in percent return per year)
- Project payback period (in years).

The model also itemizes anticipated benefits (in millions of dollars) for Year 1 (defined as the first year after project construction has been completed) and for the full twenty-year lifecycle. The calculated benefits include:

- Travel time savings
- Vehicle operating cost savings
- Accident reductions
- Emission reductions.

Exhibit II-1 provides an example of the results produced by Cal-B/C.

Exhibit II-1
Cal-B/C Results Sheet

INVESTMENT ANALYSIS
SUMMARY RESULTS

		ITEMIZED BENEFITS (mil. $)	1st Year	20 Years
Life-Cycle Costs (mil. $)	$4.0	Travel Time Savings	$0.5	$7.1
Life-Cycle Benefits (mil. $)	$8.1	Veh. Op. Cost Savings	$0.0	$0.7
Net Present Value (mil. $)	$4.1	Accident Reductions	$0.0	$0.2
Benefit / Cost Ratio:	2.0	Emission Reductions	$0.0	$0.1
Rate of Return on Investment:	15.8%	TOTAL BENEFITS	$0.6	$8.1
Payback Period:	7 years			

1.3   Parameters

Users can override default parameters to produce tailored results if more detailed information is available for specific projects. The model requires inputs on only three worksheets, but more experienced users can access the parameters and detailed calculation sheets to change default values as needed for analyses.

The last sheet in Cal-B/C (*Parameters*) contains all the economic values and rate tables used by the model. Adjusting the economic update factor using the Gross Domestic

Product (GDP) deflator changes the economic values contained in the model. Values in this sheet include the following unit costs:

- General economic values
    - Year of current dollars for model
    - Economic update factor (using the GDP deflator)
    - Real discount rate
- Highway operations measures
    - Maximum volume-capacity (v/c) ratio
    - Percent ADT in average peak hour
    - Capacity per lane (general)
    - Capacity per HOV lane
- Travel time values
    - Average hourly wage (for Transportation and Utilities industry and all industries statewide)
    - Automobile, truck, and transit
- User operating costs
    - Fuel cost per gallon
    - Non-fuel cost per mile (automobile and truck)
- Highway accident costs
    - Cost of a fatality
    - Cost of an injury (Level A Severe, Level B Moderate, Level C Minor)
    - Cost of a highway accident (fatal, injury, and PDO)
    - Statewide highway accident rates (fatal, injury, and PDO)
- Fuel consumption rates (gallons per vehicle-mile for automobiles and trucks)
- Transit accident rates and costs
    - Fatality, injury, and PDO accidents
    - Passenger train, light-rail, and bus
- Passing lane accident reduction factors
- Highway emissions rates
    - CO, NO_X, PM_{10}, and VOC
    - Automobile, truck, and bus
- Rail emissions rates
    - CO, NO_X, PM_{10}, and VOC
    - Passenger train and light-rail
- Emissions costs
    - Urban Southern California, urban Northern California, and rural California
    - Automobile, truck, and bus.

2.0 DESIGN CONSIDERATIONS

The next few sections describe the principals that guided the most recent update of the Cal-B/C model in terms of:

- Functionality
- Design Parameters
- User Interface.

2.1 Functionality

The latest update to the Cal-B/C model required several capabilities to be added to the ones found in the base model:

- *Accept inputs from other models (such as microscopic simulation, travel demand, or signal optimization)* – The base version of Cal-B/C already accepted inputs from micro-simulation and travel demand models on the model inputs page, but there was no place to enter signal optimization data. Due to the stop-go nature of traffic at signalized intersections, average speed and volume data as calculated on the model inputs page are not relevant. The data from signal optimization models should be entered in aggregate on model input page.

- *Provide standardized TMS maintenance and operating costs* – Since maintenance and operations are a large portion of overall project costs for TMS projects, standardized costs should be consulted to ensure that costs for a specific project are comparable to typical costs. The TMS Baseline Inventory provides life-cycle maintenance and operating costs in present dollars. These costs have been presented to the Department of Finance and will be updated on a regular basis. The format of the costs may change in updates, so the Cal-B/C update relies on analysts consulting the Baseline tables rather than incorporating them directly.

- *Incorporate a weaving analysis* – The updated model allows for the analysis of weaving sections using the new American Association of Highway and Transportation Officials (AASHTO) Redbook method (for auxiliary lane projects) and speed estimates derived from Texas simulations (for freeway connector, HOV connector, and HOV drop ramp projects). Speeds for the weaving vehicles are estimated on the Model Inputs Sheet. A 10-percent correction factor is applied to the AASHTO estimates. Detailed benefits for weaving vehicles are estimated separately in the detailed benefit calculations pages.

- *Allow Cal-B/C to consider safety benefits due to weaving improvements* – The research for the latest update did not find support for safety benefits due

to weaving improvements, but the Cal-B/C update includes a box to allow users to input percent changes in safety if they can be estimated externally. The default is set to zero percent.

2.2   Design Parameters

The design team considered a number of features when making changes:

- *Incorporate changes directly into the existing Cal-B/C model* – Exhibit II-2 shows different options that were considered for the model framework. After weighing the pros and cons of these options, the design team decided to add new features directly to the base Cal-B/C model rather than developing a separate model or coding a new integrated model from scratch.

Exhibit II-2
Options for Model Framework

		Cons
		• May make model overly complicated • Hard to modify
		• May produce slightly different results than existing model • Could take longer to code
		• May lead to perception that some project types receive special treatment • May treat projects differently • Not clear where to include transit projects

- *Estimate user benefits for each of the twenty years* – Many of the user benefits (i.e., non-fuel vehicle operating costs and emissions) are a U-shaped function of speed. As a result, benefits cannot be interpolated from the first and twentieth year to estimate twenty-year benefits. The base Cal-B/C model estimated benefits for each year individually (an example is shown in Exhibit II-3). The project team considered an alternate approach that interpolates benefits on the basis of four years chosen to mimic the U-shape of the speed-benefit function. This approach would reduce the size of Cal-B/C, but make the calculations

less accurate. It was decided to retain the original structure of Cal-B/C and estimate benefits for each of the twenty years individually.

Exhibit II-3
20-Year Benefit Estimation

Year	AVERAGE VOLUME (vehicles/yr)		AVERAGE SPEED (mph)		AVERAGE TRAVEL TIME (hours)		TIME BENEFIT (hours/yr)		Constant Dollars	Present Value
	Existing Facility	New Facility	Existing Facility	New Facility	Existing Facility	New Facility	Existing Users	New (Induced)		
1	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
20	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
2	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
3	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
4	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
5	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
6	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
7	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
8	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
9	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
10	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
11	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
12	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
13	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
14	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
15	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
16	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
17	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
18	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
19	0	0	55.0	55.0	0.00	0.00	0	0	$0	$0
Total										$0

- *Model more areas in the detailed user benefit calculations* – The base version of Cal-B/C included pages that perform the detailed calculations for each of the four user benefits estimated in the model. The benefits are calculated in tables, like the one shown in Exhibit II-3, for each section of the highway. The base model includes tables for single occupancy vehicles, high occupancy vehicles, and trucks on the highway and separate tables for aggregate transit calculations. Exhibit II-4 shows the areas that need to be added to accommodate ITS projects and operational improvements in the model revision.

Exhibit II-4
20-Year Benefit Estimation

Area	Time Period
Highway Section	
• Single Occupancy Vehicles	Peak and non-peak
• High Occupancy Vehicles	Peak only
• Trucks	Peak and non-peak
• Weaving Vehicles	Peak and non-peak
Aggregate Arterials	Peak only
Aggregate Ramp Section	Peak only
Aggregate Transit	Peak and non-peak

- *Expand the number of values that can be modified by the user on the Model Inputs page* – The base Cal-B/C model allowed users to adjust speed and volume inputs with detailed information from regional demand or simulation models on the Model Inputs page. This page allowed users to adjust speeds and volumes on a highway section. For the most recent update, the page was expanded to include inputs from:

  – Highway Section (add weaving vehicles)
  – Aggregate Arterials (peak period)
  – Aggregate Ramp Section (peak period).

- *Do not use macros or Visual Basic in the model* – These make the model a "black box" for the user. However, the existing macro for preparing the model for a second road was retained in the most recent update to avoid adding input boxes that are rarely used for a second highway. Visual Basic and macros were also used in the input sheets submitted by Caltrans Districts.

- *Use a higher value of time for uncertainty associated with incident management and out-of-vehicle transit waiting time* – Users value out-of-vehicle time and unexpected waiting time higher because of the uncertainty and inconvenience associated with the time. The research for the original Cal-B/C model indicated that two times the value of time is appropriate for out-of-vehicle transit waiting time. The research conducted for the development indicated that three times the value of time (a factor comparable with the one used in IDAS) is appropriate for incident management waiting time.

- *Calculate benefits and disbenefits on ramps and arterials as percentages of main freeway benefits* – Information on ramps and arterials are unlikely to be available for estimating user benefits. The updated Cal-B/C model calculated ramp and arterial benefits as a percentage of highway benefits. This approach is consistent with the one adopted for estimating benefits in the TMS Master Plan. The Cal-B/C update is also able to calculate benefits from detailed data, such as from simulation models, if available.

- *Calculate agency cost savings associated with transit TMS projects* – The Cal-B/C update includes these as cost reductions, since they are not user benefits.

2.3   User Interface

A few principals also guided changes made to the layout of the model:

- *Make sure that the original Cal-B/C and the updates appear the user as one model, regardless of the actual structure* – The update is programmed as a single model, using the original Cal-B/C as a base. Additional capabilities are added to the original model.

- *Switch the names of the "Project Information Sheet" and "Input Sheets" submitted by Caltrans Districts* – The current names are somewhat confusing. However, they were retained since, the second page of the model is called "Model Inputs" and another page called inputs might lead to more confusion.

- *Make District input sheets and the Project Information Sheet similar, but not identical* – The input sheets were made to be similar to the Project Information Sheet.

3.0   REQUIRED MODIFICATIONS TO PRIOR MODEL

This section summaries the changes necessary to incorporate the new project types and other modifications requested by Caltrans as part of the update.

3.1   Project Information Sheet

The updated Cal-B/C encompasses the most recent and 2000 revisions, and handles many more project types than before. The project list would be too long for the Project Information sheet, so users of the new model select projects from a pull-down menu rather than by placing an "X" next to the appropriate project type. This required several variables to be added to the model for the project types:

Highway Capacity Expansion
– General = "GenHwy"
– HOV Lane = "HOV"
– Passing Lane = "Passing"
– Interchange = "Intersect"
– Bypass = "Bypass"
– Pavement = "Pavement"

Transit Capacity Expansion
– Passenger Rail = "PassRail"
– Light-Rail Transit (LRT) = "LRT"
– Bus = "Bus"

Operational Improvement
– Auxiliary Lane = "AuxLane"
– Freeway Connector = "FreeConn"

– HOV Connector = "HOVConn"
– HOV Drop Ramp = "HOVDrop"
– Off-Ramp Widening = "OffRamp"
– On-Ramp Widening = "OnRamp"

Transportation Management Systems (TMS)
– Ramp Metering = "RM"
– Signal Coordination with Ramp Metering = "AM"
– Incident Management = "IM"
– Traveler Information = "TI"
– Arterial Signal Management = "ASM"
– Transit Vehicle Location (AVL) = "AVL"
– Transit Vehicle Signal Priority = "SigPriority"
– Bus Rapid Transit (BRT) = "BRT"

Several other inputs were also added to the Project Information sheet to accommodate the TMS and operational improvement project types. These inputs are described later with the modeling approach specific to each project type. Inputs added include:

- For auxiliary lanes:

  – Ramp design speed (in mph)
  – Percent of highway traffic involved in weaving (estimated as the volume in the 2 right-most lanes
  – Peak and non-peak hourly on-ramp volume (vehicles/hour)

- For off-ramp widening: same as auxiliary lanes, except on-ramp volume is not needed

- For freeway connectors weaving improvement: percent of highway traffic involved in weaving

- For freeway connectors geometric improvement: before and after design speeds entered as highway speeds

- For HOV connectors: percent of HOV traffic involved in weaving

- For HOV drop ramps: percent of HOV traffic involved in weaving (i.e., entering or exiting the freeway)

- For on-ramp widening:

  – Peak hourly on-ramp volume (vehicles/hour)
  – Number of cars per green signal at ramp meter (1, 2, 3, or dual metering strategy)

- For TMS transit projects:

    – Separate inputs for in-vehicle and out-of-vehicle travel time (with and without the project during the peak and non-peak period)
    – Annual transit agency capital expenditures with and without the project
    – Annual transit agency operating and maintenance expenditures with and without the project

In addition, rules of thumb are provided for the length of highway affected by operational improvement. For bypass projects, the interpolation of traffic volumes was changed so that the volume for Year 1 is estimated using the same percentage diversion as in Year 20.

The cost calculations on the Project Input sheet were also changed to allow the calculation of reductions in transit capital, operating and maintenance costs savings due to advanced public transit systems. The savings are calculated as the difference in transit agency costs with and without the project.

Inputs added for pavement rehabilitations projects are described in the section dedicated to those projects.

3.2   Model Inputs Sheet

In the base Cal-B/C, the Model Inputs page had speeds and volumes in Year 1 and Year 20 with and without the project for the following segments of the transportation system:

- Non-HOVs (peak period and non-peak period)
- HOVs (peak period only)
- Trucks (peak period and non-peak period).

In the most recent update, the Model Inputs sheet was expanded greatly to include the following inputs:

- Highways: weaving vehicle speeds and volumes

- Aggregate Arterials: aggregate arterial information in terms of segment length, speeds, volumes, and delays in Year 1 and Year 20 during the peak period with and without the project

- Aggregate Ramp Section: aggregate ramp information in terms of segment length, speeds, volumes, and delays in Year 1 and Year 20 during the peak period with and without the project.

The updated model uses the HCM method for estimating weaving vehicle speeds associated with auxiliary lane and off-ramp widening projects and increase the estimated speeds by 10 percent (correction factor):

$$S_R = S_{FF} - (S_{FF} - 42) M_S \qquad and$$

$$M_S = 0.321 + 0.0039 \, e^{(V_{R12}/1000)} - 0.002(L_A S_{FR}/1000)$$

- S_R = space mean speed of vehicles within ramp influence area (mph)
- S_{FF} = free-flow speed of freeway approaching merge area (mph)
- M_S = intermediate speed determination variable for merge area
- V_{R12} = sum of flow rates for ramp and vehicles entering ramp influence area in right-most two lanes (vehicles/hour).
- L_A = the length of the acceleration lane (feet)
- S_{FR} = free-flow speed of ramp (mph).

For auxiliary lanes, the new model estimates the percent weaving traffic as two divided by the number of lanes in one direction and add the ramp volume to get V_{R12}. For off-ramp widening projects, the percent weaving traffic is estimated as the percent weaving traffic as three divided by the number of lanes in one direction. For both project types, speeds for remaining traffic and for with project case are calculated in the new model using a BPR curve, which is the standard Cal-B/C method.

To estimate the speeds associated with weaving for freeway connector, HOV connector, and HOV drop ramp projects, the updated model uses the table shown in Exhibit II-5, which is adapted from research conducted in Texas.

Exhibit II-5
Speed Adjustments for Connector Projects

		HOV Conn. and Drop Ramps
0.000	1.00	1.00
0.002	0.98	0.99
0.004	0.96	0.98
0.006	0.95	0.96
0.008	0.93	0.95
0.010	0.91	0.94
0.012	0.89	0.93
0.014	0.87	0.92
0.016	0.85	0.90
0.018	0.84	0.89
0.020	0.79	0.88

		Ramps
0.022	0.75	0.87
0.024	0.71	0.85
0.026	0.66	0.84
0.028	0.62	0.82
0.030	0.58	0.79
0.032	0.54	0.76
0.034	0.50	0.73
0.036	0.48	0.71
0.038	0.47	0.68
0.040	0.47	0.65
0.042	0.47	0.62
0.044	0.47	0.60
0.046	0.46	0.57
0.048	0.46	0.54
0.050	0.46	0.51
0.052	0.46	0.48
0.054	0.45	0.48
0.056	0.45	0.47
0.058	0.45	0.47
0.060	0.45	0.47
0.062	0.45	0.47
0.064	0.45	0.47
0.066	0.45	0.47
0.068	0.45	0.46
0.070	0.45	0.46
0.072	0.45	0.46
0.074	0.45	0.46
0.076	0.45	0.46
0.078	0.45	0.46
0.080	0.45	0.45

As shown in Exhibit II-6, a box was added to include weaving safety improvements, but the value of the box is set to a default of zero percent.

Exhibit II-6
Weaving and TMS Safety Improvement Box

3.3 Results Sheet

Several changes were made on the Results sheet of Cal-B/C as part of the most recent update:

- Changed "1ˢᵗ year" to "Average Annual," and calculated as the 20-year benefits divided by 20

- Showed the hours of delay saved in terms of the average annual savings and the 20-year total savings

- Changed the label "20-Year" to "Total Over Twenty Years"

- Changed the label "Accident Reductions" to "Accident Cost Savings"

- Changed the label "Emission Reductions" to "Emission Cost Savings"

- Added calculation of per person delay.

Exhibit II-7 shows the summary results displayed in the updated model.

Exhibit II-7
Updated Cal-B/C Results Sheet

3.4 Detailed Calculations

For the most recent update, changes were also made on the pages that calculate detailed user benefits:

- Included tables for each of the areas shown in Exhibit II-4

- Multiplied estimated benefits by the TMS adjustment found in a lookup table

- For travel time benefits:

  – Added another table for out-of-vehicle transit time and calculated benefits as two times the standard value of time to capture the inconvenience and uncertainty associated with out-of-vehicle time for travelers

  – Calculated travel time benefits for incident management projects at three times the standard value of time to capture the uncertainty of non-recurrent delays for travelers

- For TMS projects, calculated benefits and disbenefits on ramps and arterials as percentages of the main freeway benefits, but allowed benefits to be calculated from detailed data, if available

- For TMS projects, eliminated induced demand calculations, if detailed ramp and arterial data are not available.

3.5   Parameters

Caltrans requested that economic parameters be updated during the most-recent model revision. The following parameters were considered for updates in the new model (note that some parameters are found on the project information sheet):

- Model Year: The model is modified so that all economic parameters are for Year 2003. For parameters without new research, prior values are updated from 2000$ to 2003$ using the GDP deflator (1.0508). This factor is from the United States Office of Management and Budget, <u>Budget of the United States Government, Fiscal Year 2004</u>, Historical Tables. Table 10.1--Gross Domestic Product and Deflators Used in the Historical Tables: 1940-2008, GDP (Chained) Price Index.

- Average Vehicle Occupancy (AVO): According to the 2000-2001 California Statewide Household Travel Survey, AVO is virtually unchanged from default in existing Cal-B/C model. The default value has been left unchanged.

- Percent Trucks: The default value of 9 percent is unchanged from the base model.

- Average Daily Traffic (ADT) in Average Peak Hour: The percent ADT in average peak hour is left at the prior value of 7.8 percent. This figure

was estimated using information from the 1991 Statewide Travel Survey. The latest statewide travel survey, the 2000-2001 California Household Travel Survey, does not have trip distribution by time of day.

- Statewide Average Hourly Wage: According to the BLS Coverage Wages and Employment Program, the average annual wage for all private industries in California was $40,937 in 2001. Statistics for later years are not available and prior years are in SIC. Using the annual wage increase factor of 3.1 percent for all California private industries from the original model documentation, the 2003 hourly wage is $20.92. Cal-B/C is updated to include this new hourly wage rate, which results in a value of time for automobile and in-vehicle transit travel of $10.46.

- Transportation and Utilities Average Hourly Wage: The BLS has changed from using SIC to NAICS. The equivalent industry to Transportation and Utilities is 48-49 Transportation and Warehousing. According to the BLS Coverage Wages and Employment Program, the average annual wage for this industry was $37,468 in 2001 in California. Statistics for later years are not available and prior years are in SIC. Using the annual wage increase factor from of 2 percent for transportation-related jobs in the original model documentation, the 2003 hourly wage is $18.74.

- Value of Time for Truck Travel: Consistent with the original model, the value of time for truck travel is estimated at 100 percent of the transportation and utilities (now transportation and warehousing) hourly wage. To this, the value of fringe benefits and other employer costs (estimated at 39 percent of base salary according to December 2003 BLS figures) and the value of cargo (conservatively estimated at $1.78, which corresponds to the value used in the FHWA HERS model) are added. This results in a value of time for truck travel of $27.83.

- Fuel Cost per Gallon: The original source of fuel cost data was the California Motor Vehicle Stock, Travel and Fuel Forecast (MVSTAFF), which is published by the Caltrans Division of Transportation System Information and includes fuel cost estimates derived from the DRI-WEFA Group. The Cal-B/C update uses a new source of fuel cost data that is more responsive to changes in prices – the American Automobile Association (AAA) Daily Fuel Gauge Report (which can be found at http://www.fuelgaugereport.com/CAavg.asp). The report is updated daily using information provided by OPIS Energy Group and Wright Express, LLC for over 60,000 self-serve stations nationwide. On the basis of this report, the updated Cal-B/C model uses a fuel cost per gallon of $1.55. This figure reflects the average of daily prices for

regular unleaded gas in California on June 3, 2004 ($2.361) and June 3, 2003 ($1.761) minus gas and sales taxes. Federal and state gas taxes are currently $0.184 and $0.18, respectively. Sales tax varies by county with a base rate of 7.25 percent. Roughly 75 percent of the state is subject to "self help," in which the county imposes an additional tax of 0 to 1 percent. To estimate gas prices for Cal-B/C, an average self-help tax of 0.5 percent is assumed. This results in the following formula for calculating fuel costs (which can be updated on a per-project basis):

Fuel cost = (two day average price/sales tax) – fed gas tax – state gas tax

OR

Fuel cost = Average($2.361, $1.761)/1.075 - 0.184 – 0.18 = $1.55

- Non-Fuel Cost per Mile: The original sources have not been revised. Updating the non-fuel costs per mile by the GDP deflator (1.0508) results in non-fuel costs of $0.173 for automobiles and $0.299 for trucks.

- Accident Costs: The original sources have not been revised. The original (2000$) economic values are updated using the GDP deflator (1.0508), resulting in the following increases in values:

  - Fatal Accident: $3,104,738 (in 2000$) to $3,262,459 (in 2003$)
  - Injury Accident: $81,572 (in 2000$) to $85,716 (in 2003$)
  - PDO Accident: $6,850 (in 2000$) to $7,198 (in 2003$)
  - Average Cost: $61,891 (in 2000$) to $65,035 (in 2003$)

- Statewide Highway Accident Rates: The original statistics are from the 1997 Accident Data on California State Highways. The rates are updated using the Statewide Travel and Accident Summary table (page 11) from the 2000 version, resulting in the following values:

  - Fatal: 1491 fatal accidents/163,556.9 million vehicle-miles (MVM) = 0.009 accidents per MVM
  - Injury: 56,024 injury accidents /163,556.9 MVM = 0.343 accidents per MVM
  - PDO: 112,846 PDO accidents /163,556.9 MVM = 0.690 accidents per MVM.
  - Non-Freeway: 1.49 accidents per MVM (from page 7 summary).

- Fuel Consumption Rates: Updated rates are from the latest California Air Resources Board (CARB) model, EMFAC2002 v2.2, April 23, 2003. The rates were created using the Burden area planning inventory option

for statewide totals using area averages. The default I/M, model years, and program constants were used, except that all vehicles were assigned to a single speed bin. The model was run multiple times – for each speed bin and for 2003 and 2023. The fuel consumption rates reflect the total daily fuel consumption divided by model VMT for each speed bin and interpolated linearly. Vehicle classes for Passenger Cars through Medium-Duty Trucks are counted as automobiles. Motorcycles and Motor Homes are also included as automobiles (the VMT contribution is negligible). Light-Heavy Truck I through Heavy-Heavy Truck are counted as trucks.

- Cost of Transit Accident Rates: The original sources have not been revised, so the prior figures are updated using the GDP deflator (1.0508).

- Rates for Transit Accident Events: The national accident rates are unlikely to have changed since the original data collection, so these values are not updated.

- Passing Lane Accident Reduction Factors: The original source has not been updated, so these factors are unchanged.

- Highway Emissions Factors: The previous version of Cal-B/C uses emissions factors from EMFAC7. The updated rates are from the latest CARB model, EMFAC2002 v2.2, April 23, 2003. The new EMFAC model provides estimates of SO_X emissions that were not previously included in Cal-B/C. The updated rates were created using the Burden area planning inventory option for statewide totals using area averages. The default I/M, model years, and program constants were used, except that all vehicles were assigned to a single speed bin. The model was run multiple times – for each speed bin and for 2003 and 2023. The emissions factors reflect statewide daily emissions divided by model VMT for each speed bin and interpolated linearly. Particulates are output as PM_{10} and hydrocarbons are output as reactive organic gas (ROG). Vehicle classes for Passenger Cars through Medium-Duty Trucks are counted as automobiles. Motorcycles and Motor Homes are also included as automobiles (the VMT contribution is negligible). Light-Heavy Truck I through Heavy-Heavy Truck are counted as trucks. School Bus and Urban Bus are counted as buses.

- Health Cost of Transportation Emissions: The original source has not been revised, so the costs are updated using the GDP deflator (1.0508).

- Passenger Train and Light Rail Emissions Factors: The original source has not been revised, so the factors remain the same as in the prior model.

- Pavement Adjustments: The original sources have not been updated, so the pavement adjustment factors remain the same.

As described in Volume 1 of the technical supplement to the Cal-B/C user's guide, the value of time for truck travel consists of the "on-the-clock" wage rate as well as fringe benefits and other employer costs. The HayGroup, a private benefit consulting firm, has been publishing the Hay Benefits Report, which is an-going study of benefits practices at large and medium sized companies, since 1969. According to the 2002 Hay survey, the median value of total employer-paid benefit costs (including statutory benefits) as a percentage of base salary is 22 percent for the United States as a whole. Another private sector study conducted by Watson Wyatt Data Services shows a median value of 22 percent for all employers.

The Bureau of Labor Statistics (BLS) collects data on employer costs for employee compensation. (Note: the BLS reports as percentages of total compensation, so figures have been converted to percentages of wages and salary.) As of its December 2003 newsletter, the BLS reported employer costs equaling 39 percent of wages and salary for private industry, which is considerably higher than the private industry surveys. The difference is explained partially by the companies included in the samples. The private surveys include larger companies that pay higher wages, so benefits are a smaller percentage of salary. The difference is also due to the inclusion of legally required benefits, such as Social Security, Federal and state unemployment insurance, and workers' compensation, that account for nearly 12 percent (the resulting 27 percent is fairly close to the 22 percent in the private surveys). While some of these benefits, such as Social Security, are not included in the private sector surveys, all of the benefits are applicable to the value of time for trucking.

According to the BLS survey, employer costs do not vary substantially by region. The cost as a percentage of wages and salary is 39 percent in the West, which is comparable to the nation as a whole. When estimated by industry, employer costs are 47 percent in the Transportation and Public Utilities Group. When estimated by occupation, employer costs are 46 percent for Transportation and Material Moving Blue-Collar Occupations. Given this range of estimates, Cal-B/C uses a value for fringe benefits of 39 percent, which corresponds to the national average across industries and including legally required benefits. This is the same source for fringe benefit information that the United States Department of Transportation (USDOT) uses for its value of time guidance.

Although not considered in the base version of Cal-B/C, the value of cargo can also contribute to the value of time for truck travel. On the basis of interest costs, cargo is fairly trivial in aggregate value. However, time-sensitive goods can contribute a substantial portion to the value of time. This occurs particularly in the portion of truck deliveries in which the cargo user (i.e., the shipper or recipient) bears excess costs for

late pickup or delivery. These excess costs apply primarily to construction and technology-based manufacturing industries and includes the following types of costs:

- User project spoilage – deliveries in which the product is no longer useful (e.g., concrete or cement arriving outside its useful life)

- Missed delivery window – pickup or delivery trips that arrive after gates or loading docks are closed (which extends delivery time by a day or leads to re-delivery costs)

- Late deliveries – deliveries that cause recipients to incur additional cargo-related costs associated with overtime pay at loading docks and/or additional just-in-time processing cost penalties.

Findings from research on the value of time for cargo varies considerably. In a recent update to the Federal Highway Administration (FHWA) Highway Economic Requirements System (HERS), the value of inventory carrying cost alone was placed at $1.78 per hour. A recently developed Montana benefit-cost analysis system adds $2 to $28 per hour for the user cost of additional cargo delay. A 1997 study by the Texas Transportation Institute uses a aggregate truck value of time equal to $45 per hour, which places $25 per hour cargo premium on the standard USDOT value of driver time alone. A study by Levinson (2003) found a similar value of $49.42 per hour for commercial vehicle operators in Minnesota. A study by DeJong (2000) found a range of values between $36 and $48 per hour. A similar range of values was found by Waters et al (1995). At the high end of estimates, a survey of freight carries by Small et al (1999) found values of freight transit time in the range of $144 to $193 per hour and costs of schedule delays of $391 per hour. The National Cooperative Highway Research Project (NCHRP) 2-18 provides additional case studies showing large values (sometimes exceeding $100 per hour) for "just-in-time" processing and scheduling benefits.

Given the very large range in estimates of the value of time for cargo, the most recent version of Cal-B/C takes a conservative approach. The new value of truck travel includes a premium for the value of cargo of only $1.78 per hour. This is the lowest value found in the literature and is constant with the recent update to the FHWA HERS model.

During the latest update, two economic parameters were also added to the model:

- Factor for incident-related value of time – This is set equal to a default of three times standard value of time, which is consistent with the factor used in the federal IDAS model. The factor can be changed by the user.

- Factor for out-of-vehicle transit waiting time – This is set equal to two times standard value of time, as documented in the original

research on the value of time provided in Volume 1 of the Technical Supplement to the User's Guide. This factor can also be changed by the user.

The most recent update added several lookup tables to the Parameters sheet of the model:

- A list of valid project types, which is linked to a pull-down menu on Project Information sheet

- Weaving speed as a function of percent weaving for freeway connector, HOV connector, and HOV drop ramp projects

- Peak-period speed, volume, ramp/arterial benefits, and total benefit adjustment for highway TMS projects

- For on-ramp widening projects, an adjustment to total ramp metering benefits. This calculation is based on the Texas graph (which is shown in Exhibit II-8) modeling the impact of ramp demand on ramp metering quality.

- Travel time benefits and agency cost reductions due to transit TMS projects.

Exhibit II-8
Impact of Ramp Demand on the Quality of Ramp Metering
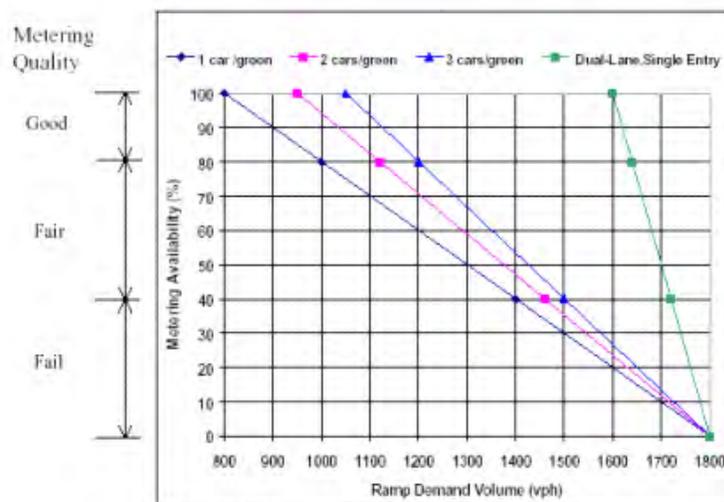
Source: Chaudhary and Messer, 2000.

The research and rationale for including the new lookup tables are described in the sections that follow.

3.6   District Input Sheets

As part of the recent model update, an accompanying workbook was developed to provide input sheets for districts to complete and provide information on projects. The workbook includes seven different sheets:

- Highway Input Sheet: General highway, HOV lane, passing lane, and pavement rehabilitation projects

- Interchange/Connector Input Sheet: interchange, freeway connector, and HOV connector projects

- Bypass Input Sheet: bypass projects

- Transit Input Sheet: passenger rail, light-rail, bus, automatic vehicle location, transit signal priority, and bus rapid transit projects

- Ramp Input Sheet: auxiliary lane, HOV drop ramp, off-ramp widening, and on-ramp widening projects

- Highway TMS Input Sheet: ramp metering, signal coordination with ramp metering, incident management, traveler information, and arterial signal management.

The workbook opens on an introductory page that has a pull-down menu to take the user to the correct input sheet by type of project. Each input sheet has a button that allows District staff to save only the applicable input sheet from the workbook, so a workbook with several blank sheets is not sent to Headquarters.

III. REVIEW OF IDAS MODEL

III.   REVIEW OF IDAS MODEL

The most-recent update to Cal-B/C expands the base model as part of Caltrans' efforts to mainstream ITS and implement the TMS Master Plan produced by the Caltrans Division of Traffic Operations. It also builds on research into the benefits of ITS sponsored by the Caltrans Division of Research and Innovation and the Federal Highway Administration's ITS Deployment Analysis System (IDAS). This section provides a review of the IDAS model and describes the identifies the portions of the model relevant to the Cal-B/C update.

The Federal Highway Administration (FHWA) sponsored the development of IDAS to assist public agencies (particularly Metropolitan Planning Organizations and other regional agencies) in integrating ITS into the transportation planning process. Regional planning decisions, including investment decisions for the Regional Transportation Improvement Program (RTIP), are often prioritized using traditional four-step planning models. Regional agencies have had trouble mainstreaming ITS because four-step models are geared towards capacity expansion and are not sensitive to many of benefits derived from ITS technologies, such as increasing the effective capacity or roadways.

For IDAS, projects were defined using user services in the National ITS Architecture. However, these user services have been modified somewhat as part of the TMS Master Plan, so the project definitions for IDAS and those in the revised Cal-B/C may differ. In addition, IDAS allows the evaluation of several projects not considered in the Cal-B/C update. The remainder of this section describes the evaluation of projects as they are defined in IDAS. These definitions are reconciled with the Cal-B/C definitions in the next section.

This section covers the methodology for evaluating several projects in IDAS including:

- *Ramp Metering* – Ramp meters are used to control the entry of vehicles onto the freeway, with a goal of maintaining safe and smooth freeway operations. IDAS includes three types of ramp metering strategies: Pre-set Ramp Metering, Traffic Actuated Ramp Metering, and Centrally-Controlled Ramp Metering.

- *Arterial Signal Management* – Arterial signal management strategies utilize advanced traffic signal controllers to coordinate intersection traffic signals along major corridors to improve mobility and operational efficiency. The specific arterial signal management improvements available within IDAS include: Isolated Traffic Actuated Signals, Pre-set Corridor Signal Coordination, Actuated Corridor Signal Coordination, and Central Control Signal Coordination. In IDAS, transit signal

priority is also included in this category. However, for the purposes of the Cal-B/C update, it is contained within the Advanced Public Transportation Systems category.

- *Signal Coordination with Ramp Metering* – This metering strategy integrates the freeway mainline and arterial facilities into a single system with metering rates chosen to optimize system-wide performance. Although IDAS does not address this strategy specifically, it can evaluate the benefits of such a system by deploying ramp metering and a signal improvement at the same time to identify synergies created by coordinated operations.

- *Incident Management* – These systems manage both special events and incidents so that the impacts to the transportation network and traveler safety are minimized. Information management systems collect and correlate data to detect and verify incidents and implement an appropriate response. The response may include traffic control strategy modifications and presentation of information to affected travelers. Incident management systems available for evaluation within IDAS include: 1) Incident Detection and Verification, 2) Incident Response and Management, and 3) Incident Detection, Verification, Response, and Management Combined. For evaluating projects in the Cal-B/C update, these management responses are combined.

- *Real Time Traveler Information Systems* – These systems allow traffic information to be disseminated to travelers and vehicles using roadway equipment (e.g., Highway Advisory Radio and Changeable Message Signs)[1] or through static or real-time interactive request/response systems (e.g., telephone, web, and kiosks). The traveler information systems available for evaluation in IDAS include: Highway Advisory Radio (HAR), Changeable Message Signs (CMS), Telephone-Based Traveler Information System, Web/Internet-Based Traveler Information System, and Kiosks.

- *Electronic Toll Collection (ETC)* – This allows travelers to pay tolls electronically and provides toll operators with the ability to detect and process violators automatically.

- *Advanced Public Transportation Systems* (APTS)– These systems provide the functions necessary to support safe and efficient movement of transit passengers and vehicles. Traffic signal prioritization communicates with roadside equipment to improve the on-time performance of transit

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[1] *Changeable Message Signs are called Dynamic Message Signs (DMS) in IDAS.*

services. Automated vehicle location enhances the information available to the transit agency and enables more efficient operations and maintenance. It also provides the capability for automated planning and scheduling of public transit operations. APTS components available in IDAS for the evaluation of fixed-route systems include: Automated Scheduling System, Automatic Vehicle Location, Combination Automated Scheduling System and Automatic Vehicle Location, and Security Systems. For paratransit systems, the available components include: Automatic Vehicle Location, Automated Scheduling System, Combined Automated Scheduling System and Automatic Vehicle Location; and Transit Vehicle Signal Priority.

The remainder of this section is structured as follows:

- *Overview of IDAS* – provides an overview of the design, scope, outputs, and terminology used in IDAS.

- *IDAS Evaluation Methodology* – summaries how IDAS estimates the impacts for each ITS improvement. Each description follows this structure:

  - *Description* – describes each ITS improvement in greater detail. Some of the ITS improvements described may not be included in the Cal-B/C update.

  - *IDAS Inputs* – identifies factors that impact the evaluation of the ITS improvement in IDAS. These are inputs potentially needed for the Cal-B/C update, but may be modified if data are not readily available.

  - *IDAS Methodology* – describes the IDAS methodology for evaluating the ITS improvement. This methodology is compared with other methodologies in the next section.

1.0   OVERVIEW OF IDAS

IDAS allows regional agencies to integrate information on ITS benefits and costs with their planning models to perform systematic trade-off analyses. The FHWA released IDAS for distribution by McTrans at the University of Florida in 2000. IDAS is currently being updated to include results from new empirical studies.

Since December of 1994, the United States Department of Transportation's Joint Program Office for Intelligent Transportation Systems has been actively collecting empirical information about the impacts of ITS projects (such as travel time savings and

accident reductions). The ITS Joint Program Office also collects information on deployment costs, which can be used for benefit-cost analysis and implementation costing. These databases are available online.[2]

IDAS was developed in tandem with the national ITS benefit and cost databases. The original literature search conducted for the development of IDAS formed the basis of the national databases. Although the ITS databases and IDAS are maintained separately, updates to either the ITS databases or IDAS are incorporated in the next update of the other.

The IDAS software provides users with three resources for conducting ITS analyses:

- *Default ITS Impact Settings:* For each ITS component, IDAS provides default settings of transportation system impacts. The default settings were set based on the empirical data found in the national ITS benefit database. These impacts are based on national experience, so the actual impacts will vary based on the actual deployment as well as local transportation supply and demand characteristics. The default settings provided by IDAS are intended to be modified as needed to reflect local transportation and traveler characteristics.

- *IDAS Equipment Database Spreadsheet:* The Equipment Database provides a comprehensive inventory of ITS equipment and costs associated with various ITS improvements. The costs are consistent with the national ITS costs database. IDAS users can apply the inventory to estimate generic ITS equipment needs and costs.

- *ITS Library:* The library catalogs documented impacts of many ITS technologies applied within the United States and internationally. The ITS Library provides specific case studies for agencies applying specific ITS technologies. The library is consistent with the national ITS databases and provides references.

By sponsoring a review of IDAS methodologies, Caltrans intends to build upon the research investments already made by the federal government. Some of the methodologies used in IDAS may be appropriate for the Cal-B/C update. However, Cal-B/C cannot adopt IDAS methodologies wholesale as the structure and intent of the two models are very different. Regional agencies tailor IDAS with their regional planning models to examine the impact of ITS strategies on the regional transportation system and chose among strategies. Caltrans uses Cal-B/C to assess the benefits and costs of a project in a given location once a specific expansion or operations strategy has

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[2] *www.benefitcost.its.dot.gov*

been chosen. Cal-B/C must be capable of assessing several projects for programming quickly and with little set-up.

Exhibit III-1 summarizes some of the similarities and differences between IDAS and the base version of Cal-B/C. The differences in particular must be considered as IDAS methodologies are chosen for incorporation into Cal-B/C. The rest of this section describes further the structure and evaluation methodologies used in IDAS.

Exhibit III-1
IDAS Compared to Cal-B/C

		Cal-B/C
		• Assess benefits and costs of a specific project in a specific location • Intended to assess a specific project • Assess projects quickly with little set-up time
		• Travel time • Vehicle operation costs • Accidents • Emissions
		20-year life-cycle
		2 freeway sections, transit
		User inputs traveler responses in terms of localized impacts and shifts in mode choice
		User supplies project-specific costs
		California-specific

1.1   Design and Scope of the IDAS Model

IDAS operates as a post-processor to four-step travel demand models used by Metropolitan Planning Organizations (MPO) and by State Departments of Transportation (DOT) for transportation planning purposes. Although it is a sketch-planning tool, IDAS implements the modal split and traffic assignment steps associated

with a traditional planning model. These steps are the key to estimating the changes in modal, route, and temporal decisions of travelers resulting from ITS technologies. Because IDAS estimates impacts at the sketch-plan level, it is intended for analyzing alternatives rather than optimizing ITS operations.

IDAS evaluates several user benefits, including changes in mobility, travel time/speed, travel time reliability, fuel costs, operating costs, accident costs, emissions, and noise. The performance of selected ITS strategies can be viewed by market sector (mode), facility type, and district. IDAS also provides benefit/cost comparison of ITS improvements individually or in combination.

IDAS includes five analysis modules, which are illustrated in Exhibit III-2:

- Input/Output Interface Module
- Alternatives Generator Module
- Benefits Module
- Cost Module
- Alternatives Comparison Module.

The Benefits Module is comprised of four sub-modules that calculate user benefits in terms of travel time/throughput, environmental impacts, safety, and travel time reliability. Although not listed, non-fuel operating costs are also included. Travel time reliability is defined as a reduction in delay caused by accidents. Reliability benefits are monetized at three times the value of travel time benefits.

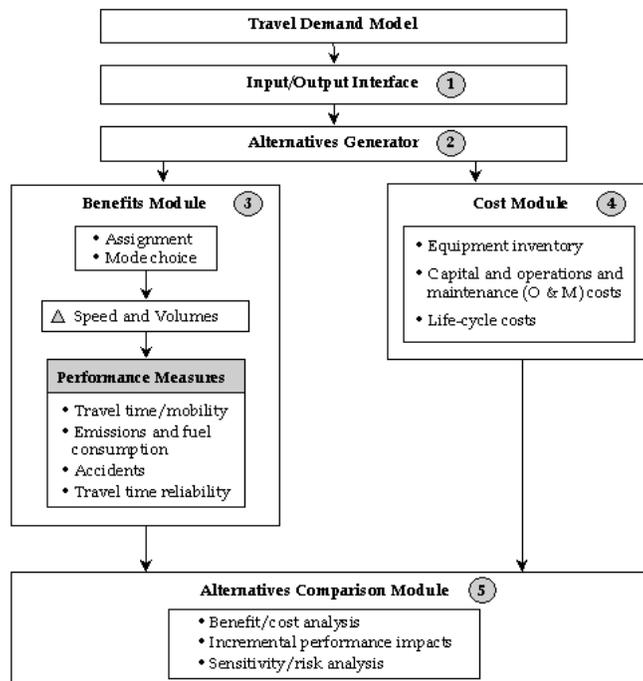**Exhibit III-2**
IDAS Model Structure

Exhibit III-3 lists ITS components that IDAS is capable of analyzing. Components considered in the Cal-B/C update are printed in black.

Exhibit III-3
ITS Components in IDAS

Regional Multimodal Traveler Information Systems (continued)
- Telephone-Based Traveler Information System
- Web/Internet-Based Traveler Information System
- Kiosk with Multimodal Traveler Information
- Kiosk with Transit-only Traveler Information
- Handheld Personal Device – Traveler Information
- Handheld Personal Device – Traveler Information with Route Guidance
- In-Vehicle – Traveler Information Only
- In-Vehicle – TI with Route Guidance

Commercial Vehicle Operations
- Electronic Screening
- Weigh-in-Motion
- Electronic Clearance – Credentials
- Electronic Clearance – Safety Inspection
- Electronic Screening/Clearance combined
- Safety Information Exchange
- On-board Safety Monitoring
- Electronic Roadside Safety Inspection
- Hazardous Materials Incident Response

Advanced Vehicle Control and Safety Systems
- Motorist Warning – Ramp Rollover
- Motorist Warning – Downhill Speed
- Longitudinal Collision Avoidance
- Lateral Collision Avoidance
- Intersection Collision Avoidance
- Vision Enhancement for Crashes
- Safety Readiness

Supporting Deployments
- Traffic Management Center
- Transit Management Center
- Emergency Management Center
- Traffic Surveillance – CCTV
- Traffic Surveillance – Loop Detector System
- Traffic Surveillance – Probe System
- Basic Vehicle Communication
- Roadway Loop Detector
- Information Service Provider Center

Generic Deployments
- Link-based
- Zone-based

The Cost Module estimates life-cycle expenditures by year and the average annual costs for ITS improvements. The costs estimated include:

- Public sector capital costs (including design and construction costs)
- Public sector operating and maintenance costs
- Private sector capital costs
- Private sector operating and maintenance costs.

On the basis of the ITS components deployed, IDAS estimates the annual stream of costs required for each ITS improvement. It also calculates an average annual cost for each ITS option using the life-cycle costs of all ITS improvements included in the analysis. The resulting average cost is used as the cost in the benefit/cost analysis.

Each ITS component is associated with a set of default ITS equipment. IDAS compiles costs based on the inventory of ITS equipment generated by IDAS for each ITS improvement. Costs for the individual ITS equipment were obtained from the National ITS Architecture and are provided as defaults in the IDAS database. The default costs in IDAS are periodically updated based upon the national ITS costs database. The user may accept this default set of ITS equipment or modify the type and quantity of equipment if local information is available.

1.2 IDAS Outputs

IDAS can be used to answer several deployment questions:

- What types of impacts/benefits result from different types of ITS components?

- What types of ITS components provide the greatest benefits for the region?

- On which facility types does the deployment of ITS components provide the greatest level of benefits?

- At which geographic locations does the deployment of ITS components provide the greatest level of benefits?

- What is the impact of combining different types of ITS components?

Four default summary sheets are output by IDAS. Three of the summary sheets provide details on the performance of the ITS option compared with a control alternative (base conditions) by facility type (freeway, expressway, arterial, ramp, etc.), and market sector (mode and/or trip purpose) or district (as identified in the regional model or by the user). The performance measures included are:

- Vehicle miles of travel (VMT)
- Vehicle hours of travel (VHT)
- Average speed
- Person hours of travel (PHT)
- Number of person trips
- Number of accidents
    - Fatality
    - Injury
    - Property damage only
- Travel time reliability (hours of unexpected delay)
- Fuel consumption (gallons)
- Emissions
    - Hydrocarbon/reactive organic gases
    - Carbon monoxide
    - Carbon dioxide
    - Oxides of nitrogen
    - Particulate matter (PM10)
    - Sulfur dioxide.

The Benefit/Cost Summary, details the results of the benefits valuation (value of time saved, value of accident reductions, etc.), cost analysis of the ITS option, net annual benefit, and benefit-cost ratio. The benefit-cost analysis is a snap-shot of the monetized benefits for the analysis year used in the model and the average annual costs associated with the ITS improvements. The summary includes:

- Annual Benefits
    - Change in user mobility
    - Change in user travel time (in-vehicle, out-of-vehicle, and travel time reliability)
    - Change in costs paid by users (fuel costs, non-fuel operating costs, and internal accident costs)
    - Change in external costs (external accident costs, HC/ROG, NOx, CO, PM10, CO2, SO2, noise, other mileage-based external costs, and other trip-based external costs)
    - Change in public agencies costs (efficiency included)
    - Other calculated benefits
    - User defined additional benefits
- Annual costs
    - Average annual private sector costs
    - Average annual public sector costs
- Net benefit (annual benefit minus annual cost)
- B/C ratio (annual benefit/annual cost).

It is important to note that the benefit-cost summary includes agency cost savings, which are considered to be agency cost savings rather than user benefits in Cal-B/C. IDAS includes other user benefits not found in Cal-B/C, such as reliability and noise.

Reliability has been the subject of a number of recent studies by the Caltrans Division of Traffic Operations, such as a recent report on measuring recurrent versus non-recurrent congestion[3] as well as analyses associated with the Highway Congestion Monitoring Program (HICOMP). The Division of Transportation System Information has also examined measuring reliability as part of the statewide performance measurement initiative. Caltrans has not yet adopted a standard definition for measuring reliability. Also, the research literature does not contain consensus on how to monetize reliability benefits. It is recommended that Cal-B/C not incorporate reliability benefits.

Noise benefits were examined during the development of Cal-B/C. As described in the technical documentation for the model, these benefits were excluded due to the difficulty measuring noise, modeling noise propagation, and monetizing benefits.[4]

1.3   IDAS Definitions

IDAS compares the performance of selected ITS strategies against "control" alternatives that are defined by the users. IDAS models the differences between the ITS strategies and the control using traveler responses as modeled in travel demand models. The analysis hierarchy for IDAS consists of projects, alternatives, and ITS options:

- *Project* – A project is the highest level of the analysis hierarchy. A project is defined by a common set of overall travel demand determinants (e.g., nodes, links, model centroid zone structure, etc.) and by a common analysis year. A project may consist of one or more alternatives.

- *Alternative* – An alternative is defined by a common set of outputs from a single travel demand model run. Capacity improvements, such as additional highway lanes, freeway ramps, or transit lines, are represented in the travel demand model output. ITS improvements are added to the alternative to create different ITS options.

- *Control Alternative* – Once the travel demand model data are input into IDAS, a control alternative that serves as the baseline for building and

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[3] *Dowling Associates, Inc., Berkeley Transportation Systems, System Metrics Group, Inc., Measuring Non-Recurrent Traffic Congestion, prepared for the California Department of Transportation Division of Traffic Operations, draft final, 2003.*

[4] *Booz·Allen & Hamilton, Inc., Hagler Bailly, and Parsons Brinckerhoff, California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C): Technical Supplement to User's Guide, September 1999.*

comparing ITS options is created. The control alternative does not contain ITS components other than those previously deployed in the network. Each alternative has one control alternative. The control alternative is subjected to analysis procedures identical to those applied to the ITS option.

- *ITS Option* – An ITS option is an ITS deployment alternative that is to be compared against other ITS options and the control alternative. An ITS option is defined by one or more ITS improvements. IDAS calculates the impacts and associated benefits, and the costs of the ITS option, in the IDAS benefits and cost modules, and compares these estimates to the control alternative in the IDAS alternatives comparison module.

Exhibit III-4 provides an example of how the analysis hierarchy can be used in evaluating scenarios as part of a transportation planning study.

Exhibit III-4
IDAS Analysis Hierarchy
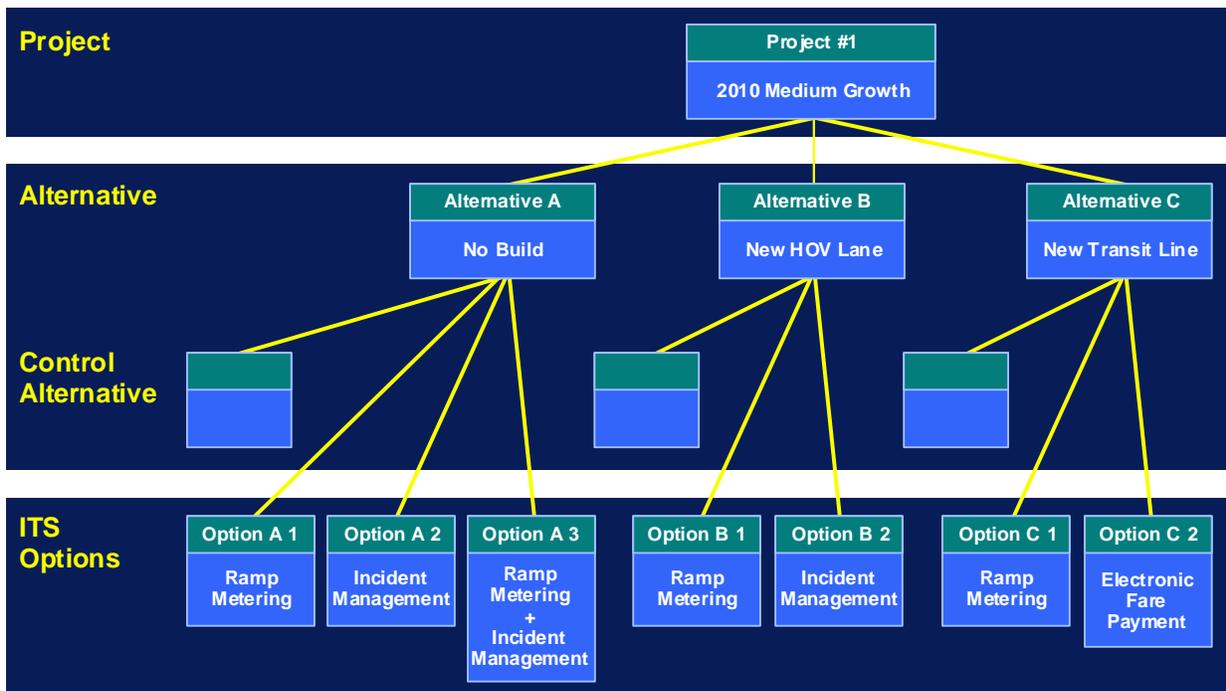
2.0   IDAS EVALUATION METHDOLOGY

The following sections describe the IDAS evaluation methodology for each ITS component considered for inclusion in Cal-B/C. The definitions of the components correspond to those used in IDAS rather than those proposed for Cal-B/C. For example, HAR and CMS are describe as separate ITS options, while deploying Real-

Time Traveler Information Systems (which can include HAR or CMS) may be a single project for the Cal-B/C update.

Each section contains the following information:

- *Description* – describes each ITS improvement in greater detail. Some of the ITS improvements described may not be included in the final Cal-B/C update.

- *IDAS Inputs* – identifies factors that impact the evaluation of the ITS improvement in IDAS. These are inputs potentially needed for the Cal-B/C update, but may be modified if data are not readily available.

- *IDAS Methodology* – describes the IDAS methodology for evaluating the ITS improvement. This methodology is compared with other methodologies in Deliverable 2b.

Many of the methodologies described take advantage of the local four-step model processes that are incorporated into IDAS when it is customized for use in particular regions. The demand model methodologies allow IDAS to capture traveler responses such as changing routes, changing modes, foregoing trips, or making new trips (induced demand). Translating the network-based IDAS methodology may not be feasible in some cases and other approaches need to be considered for Cal-B/C. Deliverable 2b reviews other approaches. For more information on network effects, please see Section 6.0 of the original technical manual for the Cal-B/C model.[5]

2.1   Ramp Metering

Description

Ramp metering is one of the most common urban congestion management techniques in use today. Ramp meters are used to control the entry of vehicles into the freeway, with the ultimate goal of maintaining safe and smooth freeway operations. IDAS includes three types of ramp metering strategies: Pre-set Ramp Metering, Traffic Actuated Ramp Metering, and Centrally-Controlled Ramp Metering.

- Pre-set Ramp Metering – Pre-set ramp metering controls the entry of vehicles onto the freeway facility according to a set schedule. It typically imposes an equal amount of delay to each vehicle at the on-ramp when the meters are in operation. It does not take into

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[5] *Booz·Allen & Hamilton, Inc., Hagler Bailly, and Parsons Brinckerhoff, <u>California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C): Technical Supplement to User's Guide</u>, September 1999.*

consideration traffic conditions on the freeway mainline or nearby arterials. The meters are typically turned on and off at scheduled times.

- Traffic Actuated Ramp Metering – This type of ramp control can adjust its metering strategy based on the freeway mainline traffic conditions. It includes both simple adaptive (strategy based on upstream traffic conditions) and corridor adaptive (considers mainline traffic conditions both upstream and downstream of the ramp). Typically, when traffic conditions are light, metering rates allow more vehicles to enter the freeway. Conversely, the meters restrict vehicles from entering the freeway if the detectors sense heavy traffic on the freeway mainline.

- Centrally-Controlled Ramp Metering – This metering strategy is intended to integrate multiple ramp meters in order to optimize system performance. The timing is coordinated from a transportation management center or ramp controllers that communicate directly with each other to determine the metering rates.

Pre-set or fixed-rate ramp metering is rarely used in California. The TMS Master Plan outlines a vision for deploying ramp metering incrementally. Under the Master Plan framework, simple adaptive ramp metering is deployed first and then metering rates are optimized. Once all the benefits possible from metering optimization are achieved, a corridor adaptive ramp metering scheme is adopted. This is followed by coordinating ramp metering with arterial signal management. The methodology adopted for Cal-B/C should be consistent with the vision outlined in the TMS Master Plan.

IDAS Inputs

IDAS requires the following information in order to evaluate ramp metering improvements:

- Ramps with meters (links)

- Freeway links affected by ramp metering

- Percent reduction in capacity for ramp links (Default: Preset Ramp Metering = 33 percent, Traffic Actuated Ramp Metering = 28 percent, and Centrally Controlled Ramp Metering = 27 percent)

- Percent increase in capacity for freeway links affected (Default: Preset Ramp Metering = 9.5 percent, Traffic Actuated and Centrally Controlled Ramp Metering = 13.5 percent)

- Accident (fatality, injury, and property damage only) rate reduction for ramp links (Default: 30 percent for all types)

- Accident (fatality, injury, and PDO) rate reduction for freeway links (Default: 30 percent for all types).

IDAS Methodology

This section describes analysis methodologies and procedures employed in the estimation of impacts resulting from the deployment of ramp metering in IDAS.

- *Link Capacity* – For ramp metering and other ITS deployments, IDAS first changes the capacity of the links affected for the ITS alternative using the IDAS default value.

- *Travel Time and Throughput* - IDAS calculates travel time/throughput impacts resulting from deployments of ramp metering by running trip assignment, mode choice, temporal choice, and induced demand for the control alternative and for the ITS option.

- *Safety* - IDAS calculates accidents including fatalities, injuries, and property damage only (PDO) for control alternative and ITS option, network-wide. The calculation is based on changes in accident rates, VMT, speed, vehicle type, and facility type.

- *Environment/Energy/Noise* - IDAS calculates emissions for types of pollutants available, and fuel consumption for control alternative and ITS option, network-wide. The calculation is based on changes in VMT, speed, cold starts, vehicle type, and facility type.

- *Travel Time Reliability* - IDAS goes through the following steps in the analysis of travel time reliability impacts resulting from ramp metering deployments:

  - Apply reduced accident rate to travel time reliability rate for the selected freeway links.

  - Calculate travel time reliability for the control alternative and ITS option, network-wide. The calculation is based on changes in VMT, volume-to-capacity ratio (v/c), and number of lanes.

  - Monetize using three times the value of travel time.

- *Benefits Estimation* – IDAS calculates the absolute and percent differences from control alternative to ITS option at the network level for all

performance measures. It then calculates the economic value of the differences.

2.2   Arterial Signal Management

Description

Arterial signal management strategies utilize advanced traffic signal controllers to coordinate intersection traffic signals along major corridors to improve mobility and operational efficiency. They include control and monitoring equipment, communication links, and the signal control equipment that support local surface street control and/or arterial traffic management. A range of traffic signal control systems are represented ranging from static pre-timed control systems to fully traffic responsive systems that adjust control plans and strategies dynamically in response to current traffic conditions and priority requests. Arterial signal management improvements available within IDAS include:

- Isolated Traffic Actuated Signals – The timing for this type of signal is influenced by vehicle detectors, but it operates in isolation from other signals. The phase of the signal is subject to a minimum and maximum green time and some phases may be skipped if no vehicles are detected. The cycle length varies from cycle to cycle. The objective is to maximize traffic flow and operations at the individual signal.

- Pre-set Corridor Signal Coordination – Pre-set corridor signal coordination involves the use of pre-timed signals that are coordinated to improve travel times along a particular corridor. Each phase of a pre-set signal has a fixed green time and change and clearance interval that are repeated in each cycle to produce a constant cycle. However, these timings are coordinated with other signals in a corridor to optimize traffic flow.

- Actuated Corridor Signal Coordination – Actuated corridor signal coordination uses the technology of traffic actuated signals but they are coordinated with neighboring signals on the corridor. The Advisory Committee for the Cal-B/C update did not specifically request that this improvement be included, but it may be possible to update Cal-B/C to consider this coordination strategy.

- Central Control Signal Coordination - This type of signal control provides the capability for traffic managers at a TMC to monitor and manage the traffic flow at signalized intersections. This capability includes analyzing and reducing the collected data from traffic surveillance equipment and developing and implementing control plans for signalized intersections. Control plans may be developed and

implemented that coordinate signals at many intersections under the
domain of a single traffic management subsystem.

- IDAS includes transit signal priority under the Arterial Signal
Coordination project type. However, transit signal priority is described
under Advanced Public Transportation Systems since it is included in
Cal-B/C as a transit option.

IDAS Inputs

In estimating impacts resulting from the deployment of arterial traffic management
systems, the IDAS methodology is based on the following parameters:

- *Variability of Travel Demand.* Travel demand at arterials varies from day-
to-day because of special events, weather conditions, changes in
directionality, or other reasons. The effectiveness of a particular traffic
management strategy can be different depending on the variability of
travel demand. For example, under highly variable demand conditions
in a corridor, actuated signal coordination is more effective than preset
signal coordination. While this information may be available at the
regional level, it is unlikely to be available for projects to be analyzed in
Cal-B/C.

- *Overall Level of Congestion.* Under high-volume/high-congestion traffic
conditions, actuated corridor signal coordination would be less effective
in a multi-regime gridlock control approach. In this case, central control
signal coordination would work better than any corridor coordination
scheme. As another example, systems with relatively low overall
volume and highly variable demand directionality may get the largest
benefit from isolated actuation.

- *Time Interval Between Signal Timing Plan Modifications.* IDAS uses this
factor to consider how closely signal timing matches optimal timing. As
more time passes between timing plan modifications, the plan deviates
more from the optimal strategy. Since Cal-B/C takes a 20-year life-cycle
approach, it is reasonable to assume that timing plans are fairly close to
optimal over the life-cycle.

- *Density of Traffic Signals.* For isolated traffic signal actuation, the density
of traffic signals is an important parameter, and a required user input in
the IDAS analysis methodology. This may not be needed for Cal-B/C if
total delays rather than delays at individual signals are considered.

The specific information requested by IDAS for arterial signal systems include:

- Intersections where located (nodes)

- Impact ranges

  - High: many special events, >20 percent demand variability in day-to-day travel
  - Medium: demand predictable, but peak direction variable or vice versa
  - Low: predictable, demand does not vary more than 10 percent day to day, peak direction consistent

- Volume-to-capacity ratio (v/c)

  - Light – v/c < 0.7
  - Moderate – 0.7 < v/c < 0.9
  - High – v/c > 0.9

- Average interval between signal timing plan modifications

  - Greater than 8 years
  - Greater than 4 years
  - Greater than 2 years
  - Updated annually
  - Updated frequently

- Density of traffic signals (only for isolated traffic actuated signals)

  - Less than 5 signals per mile
  - Greater than 5 signals per mile

- Roadways realizing improved signal progression connected to selected intersections

  - Isolated traffic actuated signals include all approach links.

  - Pre-set and actuated corridor signal coordination involve links that have improved signal progression from the first link upstream of the first intersection to the link downstream of the last intersection.

  - Central control signal coordination include the approach links to the selected intersections as well as links between any two consecutive selected intersections.

- Cross-flow links for pre-set and actuated corridor signal coordination. IDAS will reduce the capacity for all non-priority cross-flow links identified by the user. Cross-flow link capacities decrease by the same amounts as in the priority link increases. This could also be accommodated in Cal-B/C by decreasing speeds or increasing delay for the corridor.

- Capacity increase for signal approach roadways (Default: varies according to impact range, v/c, timing plan, and density selections of 8 percent to 25 percent). This could also be accommodated in Cal-B/C by increasing speeds or decreasing delay for the corridor.

IDAS Methodology

IDAS evaluates the impact of arterial signal management systems using the following approach:

- *Travel Time and Throughput* - IDAS calculates travel time/throughput impacts by running trip assignment, mode choice, temporal choice, and induced demand for the control alternative and for the ITS option using the capacity changes on the roadways input by the user.

- *Safety* – IDAS calculates the accidents including fatalities, injuries, and PDO at the network level for the control alternative and ITS option. The calculation is based on changes in VMT, speed, vehicle type, and facility type.

- *Environment/Energy/Noise* – IDAS calculates emissions including all types of pollutants, fuel consumption, and noise impacts for control alternative and ITS option, network-wide. The calculation is based on changes in VMT, speed, cold starts, vehicle type, and facility type.

- *Estimation of Benefits* - IDAS calculates the numerical and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences.

2.3 Signal Coordination with Ramp Metering

Description

Signal coordination with ramp metering is a strategy aimed at integrating both the freeway mainline and the arterial facilities as one system. Ramp metering rates are selected to optimize system-wide performance. Although IDAS does not address this specific strategy, it can evaluate the benefits of such a system by deploying ramp

metering and a signal improvement together. The regional demand model methods incorporated into IDAS accommodates synergistic effects by calculating traveler responses in terms of route diversion and mode shift due to changes in generalized cost.

IDAS Inputs

The inputs would be the same as deploying both ramp metering and arterial management systems.

IDAS Methodology

The methodology would be the same as deploying ramp metering and arterial management systems together. The ITS option would involve the capacity changes to the ramps, freeway mainline, and arterials identified by the user as well as the accident rate reductions associated with the ramp metering.

2.4   Incident Management

Description

Incident management systems handle special events and incidents so that the impact to the transportation network and traveler safety is minimized. IDAS assumes that the requisite incident detection capabilities are in place and that there is regional/local coordination with other traffic management and emergency management centers, weather service entities, and event promoters. Information from diverse sources are collected and correlated to detect and verify incidents and implement an appropriate response. The response may include modification in the traffic control strategy and providing information to affected travelers.

The same equipment assists the operator by monitoring incident status as the response unfolds. The coordination with emergency management may be through a computer-aided design (CAD) system or through other communication with emergency field personnel. The coordination can also extend to tow trucks and other field service personnel.

Incident management systems available for evaluation within IDAS include:

- Incident Detection and Verification provides the capability to traffic managers to detect and verify incidents. This process analyzes traffic sensor data, vehicle probe data, or video images for anomalies that could indicate occurrence of an incident, including video images at work zones. This capability includes analyzing and reducing the collected data from traffic surveillance equipment, including planned incidents and hazardous conditions.

- Incident Response and Management provides the capability for an incident response formulation that minimizes the incident potential, incident impacts, and/or resources required for incident management. This may include proposing and facilitating the dispatch of emergency response and service vehicles as well as coordinating response with all appropriate cooperating agencies. It provides coordination between multiple agencies before and during emergencies to implement emergency response plans and track progress through the incident. It provides vital communication linkages which provide real-time information to emergency response personnel in the field. The coordination can also extend to tow trucks and other response agencies and field service personnel.

- Incident Detection, Verification, Response, and Management Combined implements a combination of the two previous improvements. This definition corresponds closest with the one for Incident Management in the TMS Master Plan.

IDAS Inputs

IDAS requires the user to provide the following inputs to estimate the benefits of incident management systems:

- Identification of links impacted by incident detection/verification, response/management, or combinations of detection, verification, response and management

- Percent reduction in incident duration (Default: Incident Detection/Verification = 9 percent, Incident Response/ Management = 39 percent, and Combined Incident Detection, Verification, Response and Management = 51 percent). The TMS Financial Plan estimated that incident management systems would reduce incident duration on average from 33 minutes (without incident management) to 26 minutes (with existing incident management) to 22 minutes (with improved incident management).

- Percent reduction in emissions (Default: Incident Detection/Verification = 15 percent, Incident Response/ Management = 27 percent, and Combined Incident Detection, Verification, Response and Management = 42 percent). Cal-B/C estimates incident reductions as a function of speed.

- Percent reduction in fuel use (Default: Incident Detection/Verification = 15 percent, Incident Response/ Management = 27 percent, and Combined Incident Detection, Verification, Response and Management

= 42 percent). Cal-B/C estimates reductions in fuel consumption as a function of speed.

- Percent reduction in fatality rate (Default: Incident Detection/ Verification = 10 percent, Incident Response/ Management = 10 percent, and Combined Incident Detection, Verification, Response and Management = 21 percent). Cal-B/C typically calculates reductions in accident rate using changes in facility type. This option will not be available for the evaluation of incident management improvements. The TMS Financial Plan estimated a standard percent reduction in accidents based on empirical findings in the research literature.

IDAS Methodology

This section describes analysis methodologies and procedures employed in the estimation of impacts resulting from the deployment of incident management systems:

- *Travel Time and Throughput* - Direct travel time benefits resulting from the deployment of incident management components are not calculated in IDAS, since travel demand models typically do not consider non-recurring delay (caused by incidents) in their estimation of travel speeds and in their validation. Because of this, the IDAS control alternative travel times do not contain any measurement of travel time delay caused by incidents that may be used for comparison. Instead, the benefits of incident management components are captured in IDAS by focusing on improvements in travel time reliability (i.e., reduction in travel time variability) due to improved incident management. This finding is consistent with the TMS Financial Plan, which simulated the impact of different accidents and incident management on the freeway. Cal-B/C may need to adopt a reliability-style estimate of travel time benefits for incident management. The TMS Financial Plan or IDAS could be the appropriate source of data.

- *Travel Time Reliability* - IDAS goes through the following steps in the analysis of travel time reliability impacts resulting from the deployment of incident management systems:

    - Calculate travel time reliability benefits for all vehicles for the control alternative and ITS option using v/c ratios for freeway links in the network.

    - Apply the default or user modified incident duration reduction factor to the links identified (Incident Detection/Verification = 9 percent, Incident Response/

Management = 39 percent, and Combined Incident Detection, Verification, Response and Management = 51 percent).

–   Recalculate the travel time reliability for the impacted links in the ITS option using the revised incident duration value.

•   *Safety* - IDAS applies a standard reduction in fatality accident rates with an offsetting increase in injury accident rates to accommodate the reduction in incident duration time. These reductions were based on data in the ITS library found in IDAS. The TMS Financial Plan applied a reduction in the overall accident rate. Cal-B/C needs to incorporate one of these two approaches.

–   Calculate the number of fatal, injury, and PDO accidents for the control alternative and ITS option on the basis of VMT, speed, vehicle type, and facility type.

–   For each link served by incident management components, factor the number of fatality accidents by the rate identified (Default: Incident Detection/Verification = 10 percent, Incident Response/ Management = 10 percent, and Combined Incident Detection, Verification, Response and Management = 21 percent). The number of accidents factored from the fatality category is added to the number of injury accidents for the link.

–   Benefits are calculated by comparing accident figures.

•   *Environment/Energy/Noise* - IDAS goes through the following steps in the analysis of environmental impacts resulting from the deployment of incident management systems:

–   IDAS identifies the emissions and fuel consumption rates for all types of pollutants and fuel, for the control alternative and ITS option on the basis of VMT, speed, vehicle type, and facility type.

–   The ITS option emission and fuel consumption rates are reduced for the links where the improvements are deployed. These rates are reduced by 15 percent for Incident Detection/Verification, 27 percent for Incident Response/ Management, and 42 percent for combined incident Detection, Verification, Response and Management. Cal-B/C incorporates emission and fuel consumption reductions using

speed. The update could capture reductions directly or using changes in speed.

– The emissions and fuel-use figures are computed and compared to calculate benefits.

- *Estimation of Benefits* - IDAS calculates the numerical and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences.

2.5   Real-Time Traveler Information Systems

Description

Real-time traveler information systems allow traffic information to be disseminated to travelers and vehicles using roadway equipment (HAR and CMS) or through static or real-time interactive request/response systems (telephone, web, and kiosks). Careful placement of the roadway equipment provides the information at points in the network where the drivers have recourse and can tailor their routes to account for the new information. Many of these systems can provide tailored information in response to a traveler request. The traveler can obtain current information regarding traffic conditions, transit services, traveler services, rideshare/ride match, parking management, and pricing information. Successful deployment of these systems rely on the availability of real-time transportation data from roadway instrumentation, probe vehicles or other means.

The traveler information systems available for evaluation in IDAS include:

- Highway Advisory Radio – General advisory and traffic control information provided to the driver while en route over wide-area wireless communications direct to the vehicle radio.

- Changeable Message Signs – CMS are message boards placed along roadways (typically freeways). They are used to notify travelers of incidents, travel time information, construction/road closures, and other potential hazards. Careful placement of the roadway equipment provides the information at points in the network where drivers have recourse and can adjust their routes to account for the new information.

- Interactive Traveler Information Systems including Telephone-Based and Web/Internet-Based Traveler Information Systems and Kiosks – Interactive traveler information systems provide traffic or travel information in response to a travelers request. It includes both static broadcast and real-time interactive request/response information

systems. The traveler can obtain current information regarding traffic conditions, transit services, rideshare/ride match, parking management, and pricing information. A variety of interactive devices are available to access information prior to a trip or en-route including the telephone, computer, or kiosks.

IDAS Inputs

The following steps are required user inputs for the analysis of impacts associated with the deployment of real-time traveler information systems in IDAS:

Highway Advisory Radio

- Identify freeway links where HAR transmitted information will be received by travelers (one link per direction). These links should be identified to represent the estimated number of trips receiving information from the HAR.

- Average HAR usage during the time period specified (percent vehicles that tune to broadcast). Variability in travel conditions including weather, travel demand, incidents, construction, catastrophic events, and special events should be considered (Default: 5 percent).

- Percent vehicles hearing broadcast that save time. Take into account quality of traveler information (accuracy, timeliness, specificity) and driver familiarity with alternative routes (Default: 25 percent).

- Percent time that extreme traffic conditions are occurring. HAR is most useful under extreme conditions such as snow/ice events, heavy travel demand days, and major incidents (Default: 10 percent).

- Average amount of time saved by each traveler saving time for the time period specified by the model (Default: 4 minutes).

Changeable Message Signs (CMS)

- Identify link where CMS will be installed.

- Percent time sign is turned on and disseminating information that can be used to save travel time. CMS are most useful under extreme conditions such as snow/ice events, heavy travel demand days, and major incidents (Default: 10 percent).

- Percent vehicles passing sign that save time. Take into account quality of traveler information (accuracy, timeliness, specificity), variability in

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travel conditions (weather, travel demand, incidents, construction, catastrophic events, special events), and driver familiarity with alternative routes (Default: 28 percent).

- Average amount of time saved by each traveler saving time (Default: 11 minutes).

Telephone- and Web-Based Traveler Information Systems

- Identify links in the transportation network that are "in-coverage" for the information service. These are links that are "instrumented" to provide real-time traveler information to the traffic operations center.

- Market penetration defined as the percentage of travelers inquiring information from the system as they depart or en-route (Default: 0.5 percent for telephone-based and web-based in 2000; 5 percent in 2005; 10 percent in 2010; 20 percent in 2015; 30 percent in 2020; and straight-line extrapolation of these values in 2020 and beyond).

- Maximum amount of time saved by each traveler saving time (Δ_{max}), (Default: Telephone-based information systems = 15 percent of in-coverage delay time for up to 10 percent market penetration; and zero percent of in-coverage delay time for 60 market penetration or greater. web-based information systems = 20 percent of in-coverage delay time for up to 10 percent market penetration; 10 percent of in-coverage delay time for 40 percent market penetration; and zero percent of in-coverage delay time for 60 market penetration or greater).

Kiosks

- Identify centroids/zones where kiosks are to be installed

- Percent travelers looking at information as they depart in zone specified (Default: Transit-only kiosk = 5 percent of transit trips and Multimodal-traveler information kiosk = 0.5 percent of all trips)

- Percentage of travelers that may be able to save time. Take into account location of kiosk(s) relative to total size of zone, time of travel (kiosks are likely to be used more during the p.m. peak period and less during the a.m. peak period), and trip purpose (kiosks are likely to be used more by work-to-home trips and less by home-to-work trips), (Default: transit-only kiosk = 20 percent and multimodal traveler information = 40 percent of all trips).

- Average amount of time saved by each traveler saving time (Default: transit-only kiosk = 2 minutes and multimodal traveler information = 3 minutes)

IDAS Methodology

This section describes IDAS analysis procedures employed in the estimation of impacts resulting from the deployment of real-time traveler information systems.

- *Travel Time and Throughput*

  – HAR: For each market sector (mode) for the links identified with HAR deployment, multiply the traffic volume times vehicle occupancy times the HAR usage percentage times the percent time that extreme conditions are occurring times the HAR usefulness percentage times the average amount of time savings in hours. Sum over all links with HAR coverage. This is the overall estimate of person-hours saved as a result of HAR deployment.

  – CMS: For each market sector on each CMS-equipped link, multiply the traffic volume times the average vehicle occupancy times the percent time sign is turned on times the percent vehicles passing sign that save time times the average amount of time savings in hours. Sum over all CMS-equipped links. This is the overall estimate of person-hours saved as a result of CMS deployment.

  – Telephone and Web-based Traveler Information: IDAS computes the delay time associated with in-coverage links in the network, where delay time is defined as the difference between the loaded travel time and the free-flow travel time plus the incident delay calculated in the IDAS Travel Time Reliability module. IDAS accumulates the total in-coverage delay for each O-D, $\overline{d}_k$, where k is the O-D pair identifier. In this process, "in-coverage" links that are used by each O-D pair are identified and the delay associated with these links are computed (in this process IDAS uses a weighted average of multiple paths used by a single O-D). This delay by O-D pair is saved and applied to the travel time savings computed. The avoided delay for each O-D pair is computed by multiplying O-D trips times the market penetration times the in-coverage delay time times the delay savings. The avoided delay is aggregated across all O-D pairs.

- Kiosks: IDAS identifies the number of trips departing from zones where kiosks are located (by market sector). The avoided delay for each zone is computed by multiplying the number of trips originating at the zone times the percent travelers looking at information as they depart times the percent travelers that may be able to save time times the average amount of time saved. Aggregate avoided delay across all zones with kiosks is then computed.

- *Safety* – IDAS does not calculate any safety benefits for real-time information systems.

- *Environment/Energy/Noise* – IDAS does not calculate any of these benefits for real-time information systems.

- *Travel Time Reliability* - Travel time reliability impacts are taken into account in the travel time and throughput calculations.

- *Other Benefits and Costs* - No other benefits are included.

- *Estimation of Benefits* - IDAS calculates the absolute and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences. The value of time used for the calculation equals three times the standard value of time in IDAS. This is because real-time information systems are most effective under non-recurring congestion conditions. The delay incurred under such conditions is unexpected and thus more "expensive" than normal traffic delay.

2.6   Electronic Toll Collection

Description

ETC allows travelers to pay tolls electronically. It also provides toll operators with the ability to detect and process violators. Dedicated short-range communication between the roadway equipment and the vehicle is required as well as communications lines between the toll collection equipment, transportation authorities, and the financial infrastructure that supports fee collection. Vehicle tags of toll violators are read and electronically posted to vehicle owners. Standards, inter-agency coordination, and financial clearinghouse capabilities enable regional, and ultimately national interoperability for toll collection services. Toll tags and roadside readers can also be used to collect road use statistics for highway authorities. These data can be collected as a by-product of the toll collection process or collected by separate readers that are dedicated to probe data collection.

IDAS Inputs

IDAS requires the following inputs to analyze the impacts associated with the deployment of basic ETC:

- Indicate links where ETC components are located

- Number of toll booths equipped with ETC

- Total number of toll collection lanes/booths

- Capacity impact of ETC component (Default: 162 percent times the percentage of lanes/booths equipped)

- Average annual toll facility operating costs (if calculation of agency cost savings is desired). These cost should include only the operating costs for the facilities on which the directional links are identified.

- Agency cost savings (Default: 77 percent times the percentage of lanes/booths equipped and the average operating costs)

IDAS Methodology

IDAS estimates benefits associated with the deployment of basic electronic toll collection systems using the following process:

- *Travel Time and Throughput* - The impact of ETC components results in increased capacities at toll collection locations in the network. These changes in capacity are used in the assignment runs of the ITS option. From previous experience, the anticipated increase in capacity at electronic toll lanes is 162 percent. After deployment of ETC systems, the overall toll plaza capacity will become **(1.62*p+1)** times the initial capacity. The v/c ratio in the toll plaza will be **v/(1.62*p+1)*c′** where:

    – v is total volume
    – c′ is initial toll plaza capacity
    – p is percent of lanes/booths equipped with ETC. (This is the number of toll lanes/booths equipped with ETC divided by the total number of toll collection lanes/booths.)

    The toll plaza speed is calculated as a function of v/c using the IDAS speed-flow curves in the trip assignment algorithm. The assignment, mode choice, temporal choice and induced/foregone demand procedures are run for the control alternative and the ITS option. The

travel time savings for non-transit market sectors is computed by subtracting the travel time for the ITS option from the control alternative.

- *Safety* - ETC is not anticipated to have a significant impact on the number of accidents. However, there may be safety impacts based on changes in output speeds at the toll facility locations, changes in volumes, or shifts in facility types used for travel. IDAS calculates the number of fatal, injury, and PDO accidents for the control alternative and ITS option on the basis of VMT, speed, vehicle type, and facility type. Since Cal-B/C does not calculate accident rates based upon speed, the updated model may not show a safety benefit for ETC.

- *Environment/Energy/Noise* - Environmental impacts are calculated using changes in model outputs for link volumes and speeds. IDAS calculates the emissions and fuel use for the control alternative and ITS option on the basis of VMT, speed, and vehicle type. Unless the toll section covers a large area, this impact will probably be marginal.

- *Travel Time Reliability* - IDAS estimates travel time reliability for all vehicles in the control alternative and ITS option using v/c ratios, number of lanes, and VMT for freeway facilities.

- *Other Benefits and Costs* - Previous studies suggest that ETC increases the efficiency of operations at toll plazas. IDAS follows these steps in estimating reductions in agency operating costs that result from the deployment of basic electronic toll collection equipment:

  - Multiply the percentage of lanes with ETC equipment with the anticipated reduction in operating cost for that facility. IDAS uses a default reduction of 77-percent in agency operating costs.

  - Multiply the resulting figure with the user-defined operating cost for the facility to estimate the annual operating cost savings.

  - The resulting agency cost savings are included as a benefit.

- *Estimation of Benefits* - IDAS calculates the absolute and percent differences from control alternative to ITS option, network-wide for all performance measures and other benefits and costs. It then calculates the economic value of the differences.

2.7   Advanced Public Transportation Systems

Description

Advanced Public Transportation Systems (APTS) provide the functions necessary to support safe, efficient movement of transit passengers and vehicles. Traffic signal prioritization functions communicate with the roadside subsystem to improve on-schedule performance. Automated vehicle location functions enhance the information available to the transit agency and enable more efficient operations and maintenance. It spans distinct central dispatch and garage management systems and supports the spectrum of fixed route, flexible route, paratransit services, and bus rapid transit (BRT) service. The systems' interfaces allow for communication between transit departments and with other operating entities such as emergency response services and traffic management systems. It also provides the capability for automated planning and scheduling of public transit operations.

APTS components available for evaluation in IDAS include:

- Automated Transit Scheduling Systems (ATSS) perform vehicle routing and scheduling, as well as automatic driver assignment and system monitoring for transit services. This service determines current schedule performance using AVL data and provides information displays at a Transit Management Center. Static and real-time transit data are exchanged with Information Service Providers, who integrate the information with data from other transportation modes (e.g., highways, rail, ferry, and air) to provide the public with integrated and personalized dynamic schedules.

- Automatic Vehicle Location (AVL) systems monitor and manage current transit vehicle location information. The location data may be used to determine real-time schedule adherence and update the transit systems' schedules in real-time. Vehicle position may be determined either by the vehicle (through GPS) and relayed to the infrastructure or may be determined directly by the communications infrastructure. A two-way wireless communication link with a Transit Management Center is used for relaying vehicle position and control measures. Fixed-route transit systems may also employ beacons along the route to enable position determination and facilitate communications with each vehicle at fixed intervals. The Transit Management Center processes the information from the AVL system, updates the transit schedule and makes real-time schedule information available to other centers or providers.

- Combination Automated Scheduling System and Automatic Vehicle Location – This involves a combination of the previous two ITS improvements.

- Security Systems – This deployment involves an on-board security system that performs surveillance activities and warns of potentially hazardous situations. Public areas, such as bus stops, park and ride lots, and stations are also monitored using surveillance equipment. Information is communicated to a Transit Management Center using the wireless (vehicle to center) or communications line (area to center) infrastructure. Security-related information is also transmitted to emergency management systems when an emergency is identified that requires an external response.

- Transit Vehicle Signal Priority - This provides the capability for transit vehicles to request signal priority through short-range communications directly with traffic control equipment at the roadside.

The most likely APTS for inclusion in Cal-B/C are: 1) Combined Automated Scheduling System and Automatic Vehicle Location, and 2) Transit Vehicle Signal Priority.

IDAS Inputs

The impacts of transit deployments in IDAS are based upon in-vehicle and out-of-vehicle travel times between zones (origin-destination travel). The model cannot analyze transit at the link level, since it does not contain a transit network. The following steps are required inputs for the analysis of impacts resulting from the deployment of APTS in IDAS:

AVL/ATSS

- Identify zone centroids (from the travel demand model) impacted by the APTS. To estimate mode shift, IDAS requires travel time changes on a zone-to-zone basis. For each selected zone, the user needs to identify whether to include trips within, trips from, and/or trips to other zones. Only O-D zones specified will be active in the transfer of trips between market sectors (modes).

- Select market sectors (modes) that will be equipped with the ATSS and/or AVL component specified

- Total number of transit vehicles in the fleet

- Total number of transit vehicles equipped with ATSS and/or AVL

- Average capital cost per transit vehicle (Default: $225,000 for fixed-transit vehicles and $85,000 for paratransit vehicle)

- Average useful life for transit vehicles (Default: fixed-transit vehicle = 12 years and paratransit vehicle = 5 years)

- Estimate annual transit agency capital cost savings - ATSS and/or AVL deployments typically improve the efficiency of transit operations, particular a reduction in fleet size (Default: 1 percent for AVL or ATSS, and 2 percent if AVL and ATSS are deployed together)

- Annual transit agency operating cost savings - ATSS and/or AVL components are anticipated to reduce transit operating costs through more efficient management of routes, better maintenance scheduling, and administrative cost savings (Default: AVL or ATSS deployment individually = 5 percent and 8 percent savings if AVL and ATSS are deployed together)

- Travel time savings impact of component for both in-vehicle and out-of-vehicle travel times (Default: ATSS = 7 percent, AVL = 10 percent, and Combination ATSS and AVL = 15 percent)

- Percentage of vehicles using new capabilities of ATSS and/or AVL component in each zone (i.e., market penetration), default = 100 percent market penetration

Transit Security System

- Indicate which zones will be affected by transit vehicles equipped with security systems. For each selected zone, identify whether to include trips within, trips from, and/or trips to other zones or districts. Only those O-D zones specified will be active in the transfer of trips from other market sectors to the affected transit market sector(s).

- Specify market sectors (modes) affected by the deployment of the transit security system (e.g., bus, rail, etc.)

- Total number of transit vehicles in the fleet

- Number of transit vehicles in fleet equipped with transit security systems

- Number of security systems deployed at transit-related facilities (parking areas, stations, stops, and other transit-related areas, but not including transit vehicles)

- Estimated average annual number of fatalities due to crime on transit vehicles and at the transit-related facilities equipped with transit security systems

- Reduction in fatalities for incidents on transit vehicles and at transit-related facilities (Default: 10 percent reduction for both on-board transit vehicles and at transit-related facilities)

- Transit security systems may result in an increase in ridership. However, no benefits data have been found in the literature to support this relationship or the value of the expected benefit (Default: 0 percent ridership increase).

Transit Signal Priority

- Select the intersections (nodes) to be equipped with transit signal priority

- Define the continuous stretch of arterial links that have improved transit signal priority

- Select the market sectors (modes) that benefit from the transit signal priority system (e.g., bus)

- Calculate speed increase resulting from transit signal priority. No link speed decreases are assessed on the cross-links. IDAS assumes that transit preemption does not meaningfully affect cross traffic and that improvements to the flow of through traffic will wash out any cross-link travel time disbenefit (Default: 13 percent).

IDAS Methodology

This section describes how IDAS estimates benefits resulting from the deployment of transit ITS.

AVL/ATSS

- *Travel Time and Throughput* - IDAS calculates the following to analyze travel time/throughput impacts resulting from ATSS and/or AVL if ridership changes are identified by the user:

  – Trip assignment routine is run for the control alternative.

  – IDAS calculates the reduction in transit market sector travel times for the ITS option by reducing the travel times (both in-

vehicle and out-of-vehicle) by the appropriate factors identified. Before multiplication with the appropriate travel time matrices, the travel time impact factor is reduced by the market penetration rate for the component. Only trips associated with those zones affected by the ATSS and/or AVL deployment have their travel times reduced. The new travel time values are stored as the ITS option. Both in-vehicle and out-of-vehicle travel times are used in subsequent mode choice calculations.

–   The mode choice, temporal choice and induced/foregone demand procedures are run for the control alternative and the ITS option.

–   The final assignment is run for the control alternative and the ITS option with the new trip tables.

–   Travel time savings for non-transit market sectors are calculated by subtracting the travel time reported for the ITS option from the travel time for the control alternative.

–   IDAS calculates passenger-hours traveled (PHT) for the transit market sector for the control alternative and the ITS option by multiplying origin-destination pair transit volume with origin-destination pair transit travel times (in-vehicle and out-of-vehicle).

–   Benefits are estimated on the differences in travel time.

•   *Safety* – IDAS calculates the number of fatal, injury, and PDO accidents for the control alternative and ITS option using VMT, speed, vehicle type, and facility type. Additional benefits for AVL deployments may result from reduced response time in case of incidents. However, no benefits data are found in the ITS library to support this relationship or the value of the benefits.

•   *Environment/Energy/Noise* - IDAS calculates the emissions and fuel use for the control alternative and ITS option based on VMT, speed, and vehicle type.

•   *Travel Time Reliability* - IDAS calculates travel time reliability estimates for all vehicles for the control alternative and ITS option using v/c ratios, the number of lanes, and VMT before and after the deployment(s) for freeway facilities.

- *Other Benefits and Costs* - IDAS goes through the following steps in the estimation of agency cost reductions resulting from ATSS and/or AVL deployments:

  Agency Capital Cost Reductions
  – Multiply the percentage of vehicles equipped with the ATSS and/or AVL deployment (total number of transit vehicles equipped divided by the total number of transit vehicles in the fleet) with the rate of reduction in transit vehicle acquisition cost
  – Multiply the resulting figure with the total number of transit vehicles in the fleet
  – Multiply the resulting reduction in transit vehicles by the estimated cost for a transit bus
  – Divide the resulting cost by the average useful life for transit vehicles

  Agency Operating Cost Reductions
  – Multiply the average of the percentage of vehicles using new capabilities of ATSS and/or AVL component in zone (market penetration rate) for the improvement by the reduction in average agency operating costs savings
  – Multiply the resulting factor by the total annual operating cost defined by the user
  – Agency cost savings are included as a benefit.

- *Estimation of Benefits* - IDAS calculates the absolute and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences.

Transit Security System

- *Travel Time and Throughput* - The impact of transit security systems may result in an increase in ridership for the transit system. However, no benefits data have been found in the literature to support this relationship or the value of the expected benefit. Therefore, the IDAS assumes a default ridership increase of zero percent as a result of installing transit security systems. If the IDAS user has reason to believe that there would be a positive ridership increase, the user can change the default value. IDAS goes through the following steps in the analysis of travel time/throughput impacts resulting from transit security systems:

- – Increase person trip table(s) for the affected transit market sector by the user input ridership percent increase for the ITS option, for trips with origins and/or destinations within the zones specified by the user. Those shifted trips will be deducted from the non-transit trip tables for the ITS option (excluding truck trips), only for similar origins and/or destinations within the zones specified. Expand all of the vehicle trip tables (except truck trip tables) to person trips using the vehicle occupancy values input by the user. It is assumed that the trips will shift from the non-affected market sectors to those which will have transit security systems, and that trips from truck market sector(s) will not shift to transit. Increase transit trips in each of the specified origins and/or destinations, adjusted to account for market penetration. The following equation is used to determine the increase:

$$ridership\ increase \times \left(\frac{total\ number\ of\ transit\ vehicles\ equipped}{total\ number\ of\ transit\ vehicles\ in\ fleet} \right)$$

  If the user specifies "Trips within Specified Zones/Districts," transit trips with origins and destinations within the specified zones will be increased. If the user specifies "Trips From Specified Zones/Districts," transit trips with origins in the specified zones will be increased. If the user specifies "Trips to Specified Zones/Districts," transit trips with destinations in the specified zones will be increased. For each O-D pair affected, the transit trip increases from the non-transit market sector(s) are reduced using proportional values. The proportions are calculated using the total number of person trips for each of the market sector(s) not affected by the transit security system, excluding the truck market sector(s).

- – Assignment, temporal choice, induced/foregone demand, and final assignment procedures are run for the control alternative and the ITS option.

- *Safety* - IDAS calculates the number of fatal, injury, and PDO accidents for the control alternative and ITS option based on VMT, speed, vehicle type, and facility type. IDAS will also calculate the anticipated reduction in the number of fatalities (due to crime) on transit vehicles or at transit-related facilities as a result of better incident response times. This benefit is addressed under Other Benefits and Costs.

- *Environment/Energy/Noise* - IDAS calculates the emissions/fuel consumption/noise impacts for the control alternative and ITS option based on VMT, speed, vehicle type, and facility type.

- *Travel Time Reliability* - IDAS calculates the travel time reliability estimates for the control alternative and ITS option freeway facilities based on changes in v/c ratios, number of lanes and VMT.

- *Other Benefits and Costs* – IDAS computes the number of reduced fatalities (due to crime) by multiplying the percentage of equipped transit vehicles and transit-related facilities with the estimated change in fatalities due to reductions in response time for each. The savings from the reduction in fatalities are calculated by multiplying the resulting number of reduced fatalities by the dollar value for transit fatality accidents minus the value of transit injury accidents. This assumes that fatalities convert to injuries.

$$\left[\begin{array}{l}\left(\dfrac{total\ number\ of\ transit\ vehicles\ equipped}{total\ number\ of\ transit\ vehicles\ in\ fleet}\right) \quad \times \\[3em] reduction\ in\ fatalities\ on\ transit\ vehicles \quad \times \\ average\ annual\ number\ of\ fatalities\ on\ transit\ vehicles\end{array}\right] \quad +$$

$$\left[\begin{array}{l}reduction\ in\ fatalities\ at\ transit\ related\ facilities\ \times \\ average\ annual\ number\ of\ fatalities\ at\ transit\ related\ facilities\end{array}\right]$$

- *Estimation of Benefits* - IDAS calculates the absolute and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences.

Transit Signal Priority

- *Travel Time and Throughput* – IDAS computes the travel time and throughput benefits from transit signal priority based on the following steps:

  – Run trip assignment for the control alternative
  – Apply speed increases identified to the affected transit signal priority links in the ITS option
  – Run trip assignment for the ITS option
  – Calculate the ratio of the ITS option travel time over the control alternative travel time (ITS option travel time/control travel time) for each O-D pair
  – Apply this ratio to the control alternative bus transit in-vehicle time matrix to derive the ITS option bus transit in-vehicle time matrix

- – Run mode choice for the ITS option using the new bus transit in-vehicle travel time matrix, keeping the auto in-vehicle times constant between the control alternative and the ITS option. IDAS does not need to consider the automobile travel times for mode choice, because these are assumed to not change in any appreciable amount between the control alternative and the ITS option.
- – Run a final assignment for the control alternative and the ITS option with the new auto vehicle trips that consider the new mode choice shares.

- *Safety* – IDAS calculates accidents including fatalities, injuries, and PDO for control alternative and ITS option using changes in VMT, speed, vehicle type, and facility type.

- *Environment/Energy/Noise* – IDAS calculates emissions including all types of pollutants, and fuel consumption for control alternative and ITS option based on changes in VMT, speed, cold starts, vehicle type, and facility type.

- *Estimation of Benefits* - IDAS calculates the absolute and percent differences from control alternative to ITS option, network-wide for all performance measures. It then calculates the economic value of the differences.

IV. TRANSPORTATION MANAGEMENT SYSTEM (TMS) PROJECTS

IV.   TRANSPORTATION MANAGEMENT SYSTEM (TMS) PROJECTS

As part of the most recent Cal-B/C update, the project Advisory Committee identified several TMS improvements to be considered:

- *Ramp Metering* – Ramp meters are used to control the entry of vehicles into the freeway, with the goal of maintaining safe and smooth freeway operations. The Cal-B/C update will allow users to assess the benefits of implementing simple adaptive ramp metering, which is the first (and capital-intensive) stage of ramp metering identified in the Caltrans TMS Master Plan.

- *Signal Coordination with Ramp Metering* – This ramp metering strategy aims to integrate both the freeway mainline and the arterials as one system. As indicated in the TMS Master Plan, this stage occurs in later steps of implementing ramp metering. Few examples exist currently in California for testing the model, but this TMS improvement is anticipated to become more common with the adoption of Memorandums of Understanding (MOUs) and other agreements between Caltrans and local agencies.

- *Incident Management* – The Cal-B/C update will evaluate all three phases of incident management (detection, verification, and response) as a single process, consistent with the TMS Master Plan. Incident management systems manage both special events and incidents so that the impacts to the transportation network and traveler safety are minimized.

- *Real-Time Traveler Information* – Multiple field elements, such as Highway Advisory Radio (HAR) and Changeable Message Signs (CMS), allow traffic information to be disseminated to travelers and vehicle. The Cal-B/C update will evaluate all static and real-time systems as a single TMS process consistent with the Master Plan.

- *Arterial Signal Management* – Arterial signal management strategies utilize advanced traffic signal controllers to coordinate intersection traffic signals along major corridors to improve mobility and operational efficiency. Cal-B/C will consider all types of arterial signal management using output from signal optimization models:

    - *Isolated Fixed Timing Signals* – These deployments consist of single signals deployed at isolated intersections. The timing

of the signals is fixed and does not adapt to changing traffic demand and is not coordinated with other signals.

– *Isolated Traffic Actuated Signals* – The timing for these type of signals is influenced by changes in travel demand through the use of vehicle detectors, but they operate in isolation from other signals. The phase of the signals is subject to a minimum and maximum green time and some phases may be skipped of no vehicles are detected. The cycle length varies from cycle to cycle.

– *Preset Corridor Signal Coordination* – Preset corridor signal coordination involves the use of pre-timed signals that are coordinated to improve travel times along a particular corridor. Each phase of preset signals has a fixed green time and change and clearance interval that are repeated in each cycle to produce a constant cycle. Timings are coordinated with other signals in corridors to optimize traffic flow.

– *Actuated Corridor Signal Coordination* – Actuated corridor signal coordination uses traffic actuated signals coordinated with neighboring signals on the corridor.

– *Central Control Signal Coordination* - This type of signal control provides the capability for traffic managers at a Transportation Management Center (TMC) to monitor and manage the traffic flow at signalized intersections.

• *Automatic Transit Vehicle Location and Scheduling* – Automatic Vehicle Location (AVL) systems monitor and manage current transit vehicle locations. The location data may be used to determine real-time schedule adherence and update schedules in real-time. These AVL systems are often combined with Automated Scheduling Systems (ATSS) which perform vehicle routing and scheduling, as well as automatic driver assignment and system monitoring for transit services.

• *Transit Vehicle Signal Priority* – This provides the capability for transit vehicles to request signal priority through short-range communications directly with traffic control equipment at the roadside in order to maintain or improve on-time performance.

• *Bus Rapid Transit (BRT)* – Bus rapid transit is a flexible form of rapid transit that combines stations, vehicles, services, exclusive lanes and TMS into an integrated system. BRT typically features exclusive bus

lanes, traffic signal priority, low floor buses and a high boarding platform, pre-paid/electronic fare payment, and limited stops.

The project Advisory Committee suggested that the selection of projects for inclusion in Cal-B/C should be prioritized based on the prevalence of work or the outlook for future projects. Using these criteria, the Advisory Committee asked the design team to exclude two types of projects initially considered for the updated model:

- Electronic toll collection
- Transit security systems.

In addition, Caltrans anticipates that few new freeway connectors will be constructed in the near-term future. These projects could be analyzed as gap closures, so the definition of freeway connector projects for the Cal-B/C update is limited to geometric corrections and improvements to major weave sections.

The remainder of this section is structured as follows:

- *Existing Caltrans Methodologies* – describes Caltrans resources on TMS improvements, such as databases, models, design manuals and methodologies for evaluating effectiveness.

- *Other Methodologies* – reviews the way other computerized benefit-cost models handle TMS improvements.

- *Recent Research and Findings* – discusses findings from recent California Partners for Advanced Transit and Highways (PATH) research with particular emphasis on the benefits and impacts of TMS improvements.

- *Cal-B/C Methodology* – explains how each of the TMS improvements are included in the updated Cal-B/C model.

1.0   EXISTING CALTRANS METHODOLOGIES

Caltrans defines TMS as "the business processes and associated tools, field elements and communications systems that help maximize the productivity of the transportation system."[6] Caltrans has placed more emphasis on the incorporation of TMS technologies as the Department has shifted to an operations focus. As the TMS Master Plan indicates, TMS includes the technological solutions, organizational change required to implement these solutions, and the business processes that they support. The implementation of TMS (and ITS technologies) must occur in coordination with operational improvements (or minor physical corrections to the transportation system),

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[6] *California Department of Transportation, Transportation Management Systems (TMS) Master Plan, 2002, p. 9.*

which are the subject of a separate report (Deliverable 3) prepared for the Cal-B/C update.

Caltrans design elements, such as the Highway Design Manual, have begun to recognize the importance of incorporating TMS into standard practices and a separate manual has been prepared for ramp metering. The TMS Master Plan represents a step towards mainstreaming ITS technologies. The Cal-B/C update represents another.

The project team for the Cal-B/C update reviewed a number of existing Caltrans methodologies including:

- Transportation Management Systems (TMS) Master Plan, specifically the financial modeling and baseline inventory

- Highway Design Manual

- Ramp Meter Design Manual

- Caltrans Traffic Manual

- California Intermodal Transportation Management System (ITMS).

An overview of these methodologies and their relevance for the evaluation of TMS are described in the sections that follow.

1.1 Transportation Management Systems (TMS) Master Plan

Caltrans Traffic Operations Division recently developed a Transportation Management Systems (TMS) Master Plan in response to a request by the California Legislature. The TMS Master Plan outlines the Department's vision for safer and more effective operations of the state transportation system, through system management enabled by intelligent infrastructure. The report summarizes an action plan for core TMS processes and describes the expected benefits for more effective system management and improved business processes. It is intended to be the foundation for all future Feasibility Study Reports (FSR), by laying out the critical milestones for harnessing information technology for system management. The plan also commits the Department and its partners (including the California Highway Patrol, regional agencies, counties, and local cities) to demonstrate the benefits of this transformation to its partners, the Legislature and control agencies each step of the way.

According to the Master Plan, TMS are the "the business processes and associated tools, field elements and communications systems that help maximize the productivity of the

transportation system."[7] The plan establishes the principal that TMS are a critical component of an integrated system management approach to improving mobility and safety. TMS target congestion and leverage real-time information obtained from detection technologies to maximize throughput (or flows) on the transportation system.

The business process approach is a departure from the way most other agencies view TMS technologies as simply field elements and communication systems. It suggests that the benefits of TMS cannot be valued simply as one Highway Advisory Radio providing a given amount of benefit, but rather that the process of providing traveler information benefits the public. The TMS Master Plan includes estimates of the benefits and costs associated with the core TMS business processes (Ramp Metering and Arterial Signal Management, Incident Management, and Advanced Traveler Information supported by Detection). As part of mainstreaming TMS technologies, the Cal-B/C model should adopt a similar process-based approach.

The TMS Master Plan includes a vision document, a review of business processes and suggested improvements, a performance measurement framework, a financial plan, and a technology standardization plan. The TMS Financial Plan presents a deployment methodology for TMS, an analytical framework to estimate the benefits and costs of existing and planned TMS projects and infrastructure, a benefit-cost analysis based on microscopic simulations of two California corridors, and a prioritization plan for the deployment, operations, and maintenance of TMS. In addition, the Department has prepared a TMS Baseline Inventory that documents the current TMS inventory, the future planned inventory, and typical life-cycle costs for TMS field elements.

The TMS Baseline Inventory and Financial Plan are discussed further below.

TMS Baseline Inventory

The objective of the TMS Baseline Inventory is to document the TMS inventory and costs (implementation, operations, and maintenance) for field elements, communications, central applications, and information delivery systems. The inventory also justifies the continued deployment of TMS and provides estimates of additional field elements that are planned for installation by 2010.

An initial inventory was prepared in June 2001 and submitted to the California Department of Finance. The format and template for the inventory was approved through a series of meetings with the Department of Finance (DOF) Budgets, the DOF Technology Review Unit (TIRU), and the Department of Information Technology. An update to the inventory was prepared in September 2002, which contains the TMS inventory as of June 30, 2002.

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[7] *California Department of Transportation, Transportation Management Systems (TMS) Master Plan, 2002, p. 9.*

Caltrans districts helped to estimate deployment costs, annual maintenance and support costs, replacement costs, as well as life-cycles for field elements. The costs and life-cycles are intended to reflect typical deployments and reflect the best estimates available at Caltrans. These costs were used as part of the benefit-cost analysis in the TMS Financial Plan.

The Baseline Inventory identifies 57 elements. Separate fact sheets were developed for each element, which contain the following:

- System/application
- Primary business process
- Secondary business process
- Business users
- Project approvals required
- Implementation costs (estimated actual average costs for design, development and implementation)
  - Staff
  - Construction
  - Hardware
  - Software
- Annual maintenance and support costs
  - Staff
  - Maintenance contracts
  - Support contracts
  - Software life-cycle
  - Hardware life-cycle
  - Staff training
  - Materials and equipment
- Assumptions.

TMS Financial Plan

The TMS Financial Plan is intended to provide staged TMS implementation based on expected benefits and funding scenarios. The report presents an action plan for deployment anchored in business plans and quantification of the expected statewide benefits for TMS.

The Financial Plan represents contains the following elements:

- TMS Deployment Methodology – Describes the statewide methodology for deploying TMS elements in California, including specific deployment criteria.

- Traffic Simulation Methodology – Describes the methodology used to identify the potential impacts and benefits resulting from the

deployment of the TMS elements, using the guidelines presented in the previous section.

- Simulation Results – Discusses the results of the microscopic simulation of the TMS field elements using the Paramics model.

- Secondary Research Results – Validates the results of the microscopic simulation by comparing simulated performance measures against results from field evaluations.

- Benefit Analysis – Details the benefit analysis of existing and planned TMS elements in California.

- Extrapolation, Benefit-Cost Analysis, and TMS Deployment Plan – Discusses the extrapolation methodology, provides estimates of statewide impacts, presents the benefit-cost analysis results, and presents a plan for statewide deployment.

The first section of the report provides a methodology for deploying TMS field elements in California. The purpose for the methodology is to provide a basis for estimating the types, locations, and number of future TMS field element deployments in the Master Plan. The deployment criteria are also intended to be useful for Caltrans planners and engineers designing corridors with TMS deployments. Exhibit IV-1 provides a summary of the TMS deployment guidelines. These may be useful for determining in Cal-B/C the number of TMS field elements required in a particular analysis.

Exhibit IV-1
Summary of TMS Field Element Deployment Guidelines

	Deployment Guideline
Vehicle Detection	*Urban/Suburban Freeways* **–** At least one detector station per urban freeway segment or ramp, or every one-half mile of urban/suburban freeway with detectors in each lane of mainline. Other deployment considerations include near lane configuration changes, and at locations with special vehicle mixes. Priority should be given to interchanges with forecasted volume/capacity greater than 0.80. *Rural Highways* **–** At severe weather regions, segments with special vehicle mixes, and at key points along tourist routes with high-recurring congestion and/or weekend/ seasonal congestion. Priority should be given to interchanges with forecasted volume/ capacity greater than 0.80. *Arterials* **–** At all approaches of signalized intersections and mid-block between signalized intersections where adaptive signal control is required.
CCTV	*Urban/Suburban Freeways* **–** Maximum of one camera for every one mile of urban/ suburban freeway, except where geographic, geometric or weather conditions require additional coverage. Other deployment considerations include near lane configuration changes and at locations with special vehicle mixes. Priority should be given to interchanges with forecasted volume/ capacity greater than 0.80. *Rural Highways* **–** At severe weather regions, segments with special vehicle mixes and at key points along routes with high-recurring congestion and/or weekend/seasonal congestion. Priority should be given to interchanges with forecasted volume/capacity greater than 0.80.
Traffic Signal Controllers	*Urban/Suburban Arterial***s –** One per traffic signal connected to detectors at signal and mid-block. Priority should be given to arterial segments with forecasted volume/ capacity greater than 0.75, consistent with traffic signal warrants in the Caltrans Traffic Manual.
Signal Pre-emption/Priority Elements	*Urban/Suburban/Rural Arterials* **–** One per traffic signal controller at intersections with: • High emergency vehicle traffic • Near firehouses, police stations, hospitals • High bus transit vehicle traffic • Dense population/Central Business District (CBD) • Long cycle lengths
CMS	*Urban/Suburban* **–** Upstream of major freeway-to-freeway interchanges and choke points. *Rural* **–** At severe weather regions or upstream of major decision points.
HAR	*Urban/Suburban/Rural* **–** When complex messages are needed to reach the travelers, such as at construction zones and severe weather regions.
Ramp Meters	*Urban/Suburban* **–** Where forecasted volume is greater than 1,800 vehicles per hour at the rightmost freeway lane plus on-ramp, and at areas with significant merging problems (Forecasted volumes are generally obtained from regional travel demand models.). Priority should be given to already congested locations whenever possible in coordination with regional and local jurisdictions.

The Financial Plan also provides estimates of the statewide impacts of TMS using benefit-cost analysis. The analysis focuses on TMS processes rather than field elements and used a methodology derived from Cal-B/C to estimate benefit-cost ratios. The analysis resulted in rough benefit-cost calculations for each corridor statewide that were used for prioritizing investments. The benefit-cost calculations transfer the impacts estimated for a few representative simulations to similar corridors statewide. The Financial Plan has a rough estimate of the benefit-cost of full TMS deployment in each corridor. Cal-B/C could adopt these estimates to determine the benefits and costs associated with a partial deployment (for a particular TMS project) or Cal-B/C could adopt a similar procedure to calculate benefit-cost ratios from scratch.

The first step in estimating the benefit-cost ratios for the TMS Financial Plan involved creating microscopic simulations of two corridors using the Paramics model. The two corridors (I-680 in the San Francisco Bay Area and the I-405/I-5 "Wye" in Orange County) were selected because data were readily available and they seemed relatively representative. Coding simulation models is very time-consuming, so available data were binding constraints on the analysis.

Over 20 deployment scenarios were considered for each corridor to capture the benefits and potential synergies of various TMS processes. Exhibit IV-2 summarizes the scenarios modeled for 2010. Additional simulations were conducted for the 2000 base year. Also, Paramics was run multiple times for each scenario to capture different levels of travel demand for each corridor.

The modeling information was supplemented with research into documented benefits of TMS from empirical studies around the country. The supplemental research was used to validate the simulations and to get information for areas not covered by the simulations.

A database derived from the Intermodal Transportation Management System (ITMS) provided current and project highway conditions in terms of speed, volume, and accident rates that were consistent with regional planning models run by California Metropolitan Planning Organizations. Each highway segment in the database was assigned to a category based on factors thought to influence user benefits, such as the number of lanes and accident rates.

The simulations and supplemental research allowed changes in speeds, volumes, and accident rates to be calculated for each deployment scenario and highway category. These changes were used to estimate user benefits for each highway segment using a methodology derived from Cal-B/C. The before case in the analysis consisted of the current and projected conditions found in the database. The after case was estimated by applying the appropriate percent changes for the highway category to the before case condition for each highway segment.

Exhibit IV-2
Year 2010 TMS Simulation Scenarios

		Approach
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		•
		•
		•
		•
		•
		•
Arterial Management	Adaptive with traveler information	• Adaptive signal control (two sets of actuated signal timings, for normal and incident conditions) • Increase percentage of familiar drivers (to account for CMS, HAR, Internet and media traveler information)
Ramp Metering	Fixed-time	• Straight, fixed-time metering • HOV preferential lanes at all on-ramps • With and without queue control (x4 scenarios) • Aggressive and moderate queue control (I-680 only)
	Simple adaptive	• Simple adaptive metering • HOV preferential lanes at all on-ramps • With and without queue control (x4 scenarios) • Aggressive and moderate queue control (+2 scenarios)
	Corridor adaptive	• Corridor adaptive metering • HOV preferential lanes at all on-ramps • With and without queue control (x4 scenarios) • Aggressive and moderate queue control (+2 scenarios)
Combination 1	• Incident with FSP only (26 minutes incident duration) • Simple adaptive metering with aggressive queue control • CMS at major freeway-to-freeway interchanges • Adjust driver familiarity/perturbation factors	
Combination 2	• Same as Combination 1, but add adaptive arterial signal control	
Combination 3	• Same as Combination 1, but with corridor adaptive metering with aggressive queue control	
Combination 4	• Corridor adaptive metering without queue control • Adaptive arterial signal control	

Benefits were estimated for each segment. The benefit evaluation followed the Cal-B/C methodology using travel speed and traffic volume data from the micro-simulation results, and the various rates and economic values from Cal-B/C model. Safety impacts from the TMS field elements were based on secondary research. The dollar value of benefits were estimated for travel time savings, vehicle operating cost savings, emissions reductions, and safety benefits. Similar to Cal-B/C, benefits such as agency cost savings, reduced maintenance costs, and travel time reliability were not included in the analysis. Benefits were considered for freeways, ramps, and arterials in the simulation networks.

Costs were estimated using the TMS Baseline Inventory life-cycle cost and deployment estimates made by Caltrans districts using the deployment criteria. The benefits were compared to the costs contained in the business plans and an implementation prioritization scheme was developed. This scheme was used to integrate the business action plans into a comprehensive TMS action plan. The TMS Master Plan provided the following summary for the benefit-cost estimates:

- For all congested corridors that have no ramp metering currently, successful implementation of a **simple adaptive** scheme provides the highest return on investment. Other, more sophisticated ramp metering strategies cannot be implemented before the investment in ramp meters and upstream detection is completed. All these investments are allocated to the simple adaptive ramp metering strategy.

  The simple adaptive scheme is the least restrictive form of ramp metering and avoids ramp queue backups. It does so by accelerating meter rates when ramps are backed up with vehicles. It may also be the most acceptable option to local agencies that are skeptical about the benefits of ramp metering. Ramp meters and ramp detection equipment must be installed on the entire corridor. The benefit-cost ratio for this investment is 11 to 1. The total incremental life cycle costs allocated to this strategy is approximately $270 million and the life cycle benefits are estimated to be almost $3 billion.

- For all congested corridors on which simple adaptive ramp metering has already been implemented, significant benefits could be achieved by **optimizing meter rates** while still avoiding ramp backups. This requires department staff to analyze each ramp and set of ramps to derive the optimal meter rates and adjust their current configurations accordingly. This step does not require any incremental capital costs, although it does require significant research and analysis. The benefit-cost ratio for this strategy is close to 17 to 1. However, it requires significant human resources to analyze and adjust ramp configuration rates continuously. Also, this strategy cannot be deployed until the simple adaptive ramp metering strategy has been implemented. The

total incremental life cycle costs allocated to this strategy is approximately $30 million and the life cycle benefits are estimated to be almost $500 million.

- For severely congested corridors that already have simple adaptive ramp metering and optimized meter rates, additional incremental benefits can be achieved by implementing an **extended adaptive scheme** or, better yet, a **corridor adaptive ramp metering scheme**. Both require additional investment in detection over and beyond the detection required by the simple adaptive scheme. However, the associated benefits far exceed the costs if implemented correctly. Both algorithms can be configured to minimize backups on the ramps. The benefit-cost ratio for these investments is 13.5 to 1. It requires additional investment in detection, but is very beneficial for corridors with multiple bottlenecks.

  The total incremental life cycle costs allocated to this strategy is approximately $270 million and the life cycle benefits are estimated to be more than $3.5 billion. This strategy yields these types of benefits only on severely congested corridors.

- Implementing **advanced arterial signal actuation strategies** also provides benefits that exceed the associated costs. However, the highest benefits are achieved when State-controlled arterial signals are integrated with locally controlled arterial signals and freeway ramp meters. This requires significant coordination and software integration efforts on the part of the Department and its local partners. The benefit-cost ratio for the associated investments is 4.5 to 1 and requires additional investment in arterial detection. The total incremental life cycle costs allocated to this strategy is approximately $120 million and the life cycle benefits are estimated to be more than $550 million

- Implementing **improved incident management** yields lower benefits than the other strategies. However, given that safety benefits were excluded from the benefit-cost analysis, and given that the additional field equipment related to these improvements also yields benefits related to traveler information, security preparedness and AMBER alert implementation, it is still a valuable investment. Also, many benefits related to improved coordination, partnerships, communications, and training all provide benefits that are not included.

  The benefit cost ratio for the associated investments is approximately 3 to 1 and requires investments in closed circuit televisions and changeable message signs. The total incremental life cycle costs

allocated to this strategy is approximately $1 billion and the life cycle benefits are estimated to be almost $3 billion.

- Implementing **comprehensive traveler information** is only effective when the majority of a given region (e.g., county) is covered with detection, closed circuit televisions, and changeable message signs. The additional costs for sharing the data and developing tools to share information and travel options directly with the public are relatively small compared to the costs of deploying field elements. The Master Plan assumes that the benefits for traveler information are not achieved until appropriate field element deployments are completed.

  The benefits of this investment far exceed its costs (over 100 to 1) primarily because it builds on investments allocated to the other TMS processes. However, it requires almost full coverage of field elements before the benefits can be achieved. The total incremental life cycle costs allocated to this strategy is approximately $20 million and the life cycle benefits are estimated to be more than $2 billion.

1.2   Highway Design Manual

The *Highway Design Manual* establishes uniform policies and procedures for highway design in California. The manual is organized into 25 chapters. Each chapter is updated separately to take into account new design considerations.

The most appropriate chapters for the analysis of TMS elements are: Chapter 400 (Intersections at Grade) and Chapter 500 (Traffic Interchanges). Both chapters were last updated November 1, 2001. Chapter 400 is more relevant for the analysis of traffic signals at intersections, while Chapter 500 provides guidance for ramps and ramp metering.

The manual contains design standards for ramps including design speed, lane widths, shoulder widths, lane drops, lane additions, and ramp metering. For example, the manual recommends that the ramp meter system should provide adequate storage for queues. Ramp designers should make every effort possible to meet the recommended storage length and minimize the impacts on local streets. Whenever feasible, ramp metering storage should be contained on the ramp either by widening or lengthening it. The manual provides additional guidance on the number of lanes needed to handle different ramp meter flows. Chapter 400 identifies design factors for intersections and effective signal control.

1.3   Ramp Meter Design Manual

Caltrans developed the *Ramp Meter Design Manual* to provide designers, consultants, and local agencies that perform design work on State highways, a document that

addresses the policies, design standards, and practices for the design and operation of new or existing ramp meters. It includes discussions of the design of metered ramps, ramp meter hardware necessary, and signing and pavement markings. The manual provides guidance for the analysis of on-ramp storage capacity and off-ramp capacity.

The manual recommends that geometric ramp design for new facilities should be based on projected peak-hour traffic volumes 20 years after completion of construction and operational improvement projects should be based on current peak-hour traffic volumes (less than two years old). If ramp volumes are less than 900 vehicles per hour (vph), a single-lane design can be used. When volumes exceed 900 vph, a two- or three-lane ramp should be provided. If truck volumes exceed five percent with an ascending ramp of three percent or ramp volumes exceed 1,500 vph, auxiliary lanes should be provided beyond the ramp convergence point.

Providing adequate queue storage is also an important design consideration. Ramp meter flow rates typically range from 240 to 900 vph. Ramp meter storage should be contained on the ramp through widening or lengthening if necessary. The manual states that an HOV preferential lane shall be provided at all ramp meter locations. Enforcement and operations/maintenance pullout areas should also be provided.

With respect to equipment, the meter should include the appropriate signalization, controllers, loop detectors, communications equipment, and advance warning signs.

The *Ramp Metering Policy Procedures* contained in the Appendix indicate that ramp metering reduces congestion by:

- Maintaining more consistent freeway throughput

- More effectively utilizing the capacity of the corridor

- Providing incentives for increased use of carpools, vanpools, and transit through the HOV preferential lanes.

Other benefits include reductions in accidents and air pollution.

Each District is responsible for preparing a Ramp Meter Development Plan (RMDP) identifying the freeway segments that are expected to be metered within the next ten years. In addition, existing interchange modification and new interchange projects should include provisions for ramp meters.

The manual is intended for use at the design or operations level and does not include methods for estimating the effectiveness of ramp metering. However, one of the appendices includes a method for estimating the maximum queue, total delay, total vehicles delayed, and average delay using an arrival discharge chart.

1.4   Caltrans Traffic Manual

The Caltrans *Traffic Manual* provides guidance on specifications and warrants for signal systems and for installation of other traffic control devices. Chapter 9 (Traffic Signals and Lighting) includes guidance on traffic control signals, ramp metering signals, and priority control for traffic signals. The manual indicates that traffic control signals have the following benefits:

- Provide for the orderly movement of traffic
- Increase capacity of the intersection
- Reduce frequency of certain types of accidents
- Can be coordinated for more continuous movement of traffic
- Permit cross traffic onto the major street.

The justification for the installation of traffic signals is based on warrants contained in the manual and in the *Manual on Uniform Traffic Control Devices* published by FHWA. Signal warrants are based on the following data:

- Number of lanes
- Vehicle volume per hour on major street and cross street
- Pedestrian volume
- School areas
- Accidents
- Delay.

The manual provides guidance on the costs to include for the signal project. Costs are to be shared with the local agency. The costs should include design, construction, engineering services, encroachment permits, as well as operations and maintenance.

The type of signal operation to be used is based primarily on the demand. Pre-timed and traffic-actuated (full- or semi-traffic actuated) are the two general types considered. Pre-timed and semi-traffic actuated operation should be used for coordinated corridors and should not be installed at isolated intersections. Coordination should be considered where the signalized intersections are less than 0.8 kilometers apart.

1.5   California Intermodal Transportation Management System (ITMS)

The Intermodal Transportation Management System (ITMS) is a planning decision support tool for evaluating the performance of California's transportation network and facilities. It is used to identify deficiencies in the system, develop actions to mitigate these deficiencies, and evaluate effectiveness using performance measures. The tool contains a database of current and forecast future person and freight demand by corridor, facility, and mode, includes a mode shift-model, and uses geographic information system (GIS) capabilities. Demand for person movements comes from

regional demand models maintained by Metropolitan Planning Organizations (MPOs) throughout California.

The analytical process involves the following steps:

- **Identify planning area(s) for analysis** – The user selects the planning area and map view desired including boundaries, modes, and facility types. The ITMS contains the geometric data, features, operational data, capacity, safety, utilization, and demand data associated with these spatial entities.

- **Locate deficiencies** – The ITMS will locate deficiencies based on several default (or user modified) deficiency analysis variables including congestion, posted speed, weight limits, and geometric constraints. Deficiencies are highlighted on the map in red.

- **Develop actions and strategies** – The user then identifies improvement strategies to address the deficiencies. These include infrastructure improvements (add lane, HOV lane, bus lane, etc.), transit service changes, technology improvements (ramp metering, CMS, weigh-in-motion, ETC, ATIS, or other ITS), and policy changes (congestion pricing, fare changes, speed or weight limit changes, increased fuel cost). The ITMS can address the actions independently or collectively. The user is expected to identify reasonable strategies.

- **Evaluate performance impacts** – The ITMS person mode shift model is invoked based on the strategies/actions. The factors affecting the shift includes changes in access or terminal time or price, travel time, or travel price. These are entered into the tool as a part of the action specification. The mode shift model is a quick response tool, not a demand forecast as in a traditional travel demand model. The ITMS then computes the various performance measures. The measures included are:

  Economic measures – jobs supported by transportation operating and capital expenditures, gross state product (GSP) impacts
  Environmental measures – fuel consumption, green house emissions, mobile source emissions (CO, HC, NOx, PM, total)
  Financial measures – capital cost, operating costs, and annual equivalent cost to service provider, annual equivalent cost to transportation system users
  Mobility measures - person throughput, total person miles traveled (PMT) impacted, total vehicle miles traveled (VMT) impacted, lost time due to congestion
  Safety measures – accidents and deaths.

- **Print reports** – The user can then print and plot results.

The ITMS contains a comprehensive database of facilities and travel demand and is one of the few integrated sources available statewide. The TMS Master Plan used the ITMS database as an input for the state-level analysis of TMS benefits and costs in the Financial Plan. The ITMS database may be a source for the evaluation of TMS elements in the Cal-B/C update.

2.0   OTHER METHODOLOGIES

As TMS projects are mainstreamed into the decision-making process for transportation investments, TMS must compete with traditional capacity-expansion projects for funding. Since the federal government began TMS deployment programs in the early 1990s, a considerable amount of empirical data has been collected through field operational tests (FOTs). Much of this information is collected in the TMS benefit and cost databases that are updated with IDAS.

This section highlights some of the methodologies and tools (other than IDAS) used nationally for evaluating the benefits and costs of TMS investments:

- Benefit-cost or sketch plan models
- Deterministic (Highway Capacity Manual-based) tools
- Travel demand models
- Signal optimization models
- Simulation models.

In addition to IDAS, which is the subject of Deliverable 2a, the first two sets of tools are the most likely to provide methodologies for incorporation into Cal-B/C and these are highlighted in the rest of this report. There are a number of computerized benefit-cost models for the analysis of transportation projects, but most do not handle TMS investments very well. The Highway Capacity Manual provides deterministic procedures used by engineers to design facilities and analyze operational impacts. These procedures are automated in the Highway Capacity Software (HCS), but cannot model complicated traffic dynamics.

As summarized in Exhibit IV-3, the other tools (with the exception of travel demand models) allow for more complex analysis specific to the operational impacts of TMS projects. However, these tools are very data intensive, can take a long time to calibrate, and do not provide benefit-cost analyses.

The traditional four-step travel demand models used by planners to analyze regional impacts do not consider the effect of TMS elements on capacity and traffic flow. As a result, travel demand models do not capture TMS benefits very well.

Exhibit IV-3
Relevance of Tools for TMS Analysis

	Analysis Tools and Methodologies						Microscopic Simulation Models
Ramp Metering	●	○	◐	●	●	●	●
Arterial Signal Management (single signal)	○	●	○	●	●	●	●
Arterial Signal Management (signal coordination)	◐	○	◐	●	●	●	●
Incident Management	◐	◐	○	○	●	●	●
Real-Time Traveler Information Systems	◐	○	○	○	○	◐	◐
Electronic Toll Collection	◐	○	○	○	○	○	●
Advanced Public Transportation System	◐	○	○	○	○	○	◐
Bus Rapid Transit	◐	○	◐	○	○	○	◐

Note:　● – The specific context is generally addressed by the corresponding analysis tool/ methodology.
　　　◐ – Some of the analysis tools/methodologies may address the specific context and some do not.
　　　○ – The particular analysis tool/methodology does not generally address the specific context.

Adapted from the FHWA's Decision Support Methodology for Selecting Traffic Analysis Tools

Signal optimization models and simulation models help engineers conduct what-if analyses for corridors with complicated operational geography and TMS elements. When available, they can provide more detailed engineering analysis than the rules of thumb that can be incorporated into Cal-B/C. These models are often run prior to other benefit-cost models and could be run as pre-processors for Cal-B/C.

A brief description of signal optimization and simulation models follows for readers not familiar with them. After this description, the remainder of this section is organized as follows:

- Section 3.1 provides an overview of specific benefit-cost models and the Highway Capacity Manual.

- Sections 3.2 to 3.8 describe by TMS project the analysis methodologies used in these models.

Signal Optimization Tools

Signal optimization methodologies are largely based on procedures from the Highway Capacity Manual. The tools are primarily designed to develop optimal signal phasings

and timing plans for isolated signal intersections, arterial streets, or signal networks. This may include capacity calculations, cycle length, and splits optimization including left turns, as well as coordination/offset plans. Some optimization tools can also be used for optimizing the ramp metering rates for freeway ramp control. The more advanced traffic optimization tools are capable of modeling actuated and semi-actuated traffic signals, with or without signal coordination. Examples of traffic optimization tools include SYNCHRO, PASSER, and TRANSYT-7F. These models typically output appropriate signal phases, travel time, speed, and delay by travel movement.

Simulation Models

Simulation tools are effective in evaluating the impact of traffic flows on congestion. By dividing the analysis period into time slices, a simulation model can evaluate the buildup, dissipation, and duration of traffic congestion. By evaluating systems of facilities, simulation models can evaluate the interference that occurs when congestion builds up at one location and impacts the capacity of another location.

Simulation tools, require a lot of input data, considerable error checking, and the manipulation of a number of potential calibration parameters. Simulation models cannot be applied to a specific facility without the calibration of model parameters to field conditions, which may require substantial data collection.

Simulation models assume "100-percent safe driving," so they are not effective at predicting how changes in design might influence the probability of collisions. In addition, simulation models do not take into consideration how changes in the roadside environment (i.e., visibility obstructions or roadside distractions, such as a stalled vehicle) affect driver behavior within the modeled right-of-way.

Exhibit IV-3 refers to three types of simulation models:

- *Macroscopic simulation models* – Macroscopic simulation models are based on deterministic relationships of flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic simulation models were originally developed to model traffic in distinct transportation sub-networks, such as freeways, corridors (including freeways and parallel arterials), surface-street grid networks, and rural highways. They consider platoons of vehicles and simulate traffic flow in small time increments. Macroscopic simulation models operate on the basis of aggregate speed/volume and demand/capacity relationships. Validation of macroscopic simulation models involves replication of observed congestion patterns. Freeway validation is based on both tachometer run information and speed contour diagrams constructed for the analysis periods, which are then aggregated to provide a "typical" congestion pattern. Surface street

validation is based on speed, queue, delay, and capacity information. Macroscopic models have considerably less demanding computer requirements than microscopic models. They do not, however, have the ability to analyze transportation improvements in as much detail as microscopic models, and do not consider trip generation, trip distribution, and mode choice in their evaluation of changes in transportation systems.

- *Mesoscopic simulation models* – Mesoscopic models combine properties of both microscopic (discussed below) and macroscopic simulation models. As in microscopic models, the unit of traffic flow is the individual vehicle for mesoscopic models. Similar to microscopic simulation models, mesoscopic tools assign vehicle types and driver behavior, as well as their relationships with the roadway characteristics. Their movement, however, follows the approach of macroscopic models and is governed by the average speed on the travel link. Mesoscopic model travel prediction takes place at an aggregate level, and does not consider dynamic speed/volume relationships. Mesoscopic models provide less fidelity than microsimulation tools, but are superior to regional travel demand models.

- *Microscopic simulation models* – Microscopic models simulate the movement of individual vehicles using theories of car-following and lane-changing. Vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process), and are tracked through the network on a second-by-second basis. Upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type. The traffic operational characteristics of each vehicle are influenced by vertical grade, horizontal curvature, and super-elevation, based on relationships developed in prior research. The primary means of calibrating and validating microscopic simulation models is through the adjustment of driver sensitivity factors (such as driver aggressiveness and lane changing propensity). Computer time and storage requirements for microscopic models are large, usually limiting the network size and the number of simulation runs that can be completed.

2.1   Description of Benefit-Cost Models and the Highway Capacity Manual

The next few pages provide an overview of the five benefit-cost models that may provide procedures useful for incorporation into Cal-B/C:

- SCReening Analysis for ITS (SCRITS)
- Surface Transportation Efficiency Analysis Module (STEAM)
- Sketch Planning Analysis Spreadsheet Model (SPASM)
- IMPACTS

- Highway Economic Requirements System (HERS) Operations Preprocessor.

The Highway Capacity Manual, which provides deterministic methods used by engineers for analyzing system performance, is also described.

Exhibit IV-4 shows how these six methods vary in their assumptions, networks analyzed, and benefits included. Exhibit IV-5 provides a more detailed comparison of how the models analyze particular TMS strategies and their applications.

SCReening Analysis for ITS (SCRITS)

SCRITS is a sketch-planning tool tailored for preliminary, "early-stage" analyses of ITS benefits.[8] It can be employed in a focused ITS analysis, a corridor/sub-area transportation study, or within the context of a regional planning analysis. SCRITS is an Excel worksheet that includes baseline data, a total of 16 ITS components, and lookup tables of values used to generate output calculations. The format allows users to include additional ITS applications, perform different calculations, and modify existing formulas and lookup tables. It also offers flexibility in geographic and facility coverage, provided that the user supplies a baseline consistent with the coverage being analyzed.

SCRITS is designed to be compatible with travel demand models and simulation applications. The analysis performed by SCRITS builds on the initial outputs of these tools, although some ITS applications require independent estimates of variables such as changes in vehicle-miles traveled (VMT) or vehicle-hours traveled (VHT).

SCRITS performs daily analyses on most ITS components. Peak hour or peak period analyses are limited to ramp metering. Analyses are founded largely on weekday travel data, and calculations that estimate benefits for the full week are also included. In comparison, the Cal-B/C model is based on peak period versus off-peak conditions.

SCRITS is unable to conduct detailed analyses performed by more sophisticated tools (i.e., travel demand or simulation models). SCRITS focuses on user benefits only, not benefits that accrue to agency operations, similar to Cal-B/C. Additionally, users are asked to supply and test a range of input assumptions via sensitivity analyses. In spite of these limitations, the advantages of SCRITS include simplicity, flexibility for adapting the tool's format, and ability to identify variables that can influence the benefits and overall structuring of the analysis.

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[8] *Source: User's Manual for SCRITS, SCReening Analysis for ITS; Prepared by SAIC; January 1999.*

Exhibit IV-4
Summary of Model Methodologies

						HCM 2000
Purpose	Spreadsheet based, sketch-planning tool for preliminary analysis of ITS benefits	Transportation/ economic impact analysis tool for system-wide analysis of alternative transportation investments	Sketch-planning, spreadsheet model for analyzing packages of transportation actions	Spreadsheet software for estimating the impacts of urban transportation alternatives	Computer model designed to estimate the costs, benefits, and national implications associated with various highway investments	Document that provides techniques for estimating LOS and capacity for transportation facilities
Network	Regional, corridor, facility, or subarea	Network level	System and corridor level	Single facility or corridor	Corridor level (HPMS database)	Point and segment, guidance for corridor and areawide
Time period	Mostly daily, peak hour, or peak period for ramp metering	Average weekday, peak, or off-peak	Peak and off-peak	Average weekday	Corridor	Mostly hourly
Benefits included	VHT, VMT, emissions (CO, NOx, HC), vehicle operating costs, energy consumption, accidents	Travel time, total transportation cost, accessibility to jobs, emissions (HC, CO, NOx), energy use, noise and other external costs, accidents, revenue transfers	Travel time, operating costs, out-of-pocket costs, total transportation cost, emissions (HC, CO, NOx), energy use	Travel time, out-of-pocket costs, induced demand, accident and parking costs, revenue transfers, fuel consumption, emissions	Travel time, operating costs, safety, agency costs, emissions	Speed, delay, travel time
Life-cycle	An analysis year	An analysis year	An analysis year	An analysis year	Yearly up to 20 years (mid-point of funding period to mid-point of subsequent funding period)	NA
Lookup tables	Ratio of incident VHT to non-incident VHT, emission rates, annualization factors, operating cost rates, speeds associated with AWOT/C ratios for freeway and arterials	Speed models to account for incidents, peak spreading and day-to-day variations, crash rates, emission rates, noise, global warming, and other external costs, fuel consumption, values for monetizing benefits, fuel tax rates	Emission rates, fuel consumption rates, values for monetizing benefits	Not internal to spreadsheet (used charts and tables from NHI Course No. 15257 "Estimating the Impacts of Urban Transportation Alternatives")	Deficiency levels, design standards, improvement costs, truck growth factors, crash rates, highway performance goals, fleet disaggregation factors, values for monetizing benefits, operating costs, state cost factors, emission rates	Various adjustment factors

Exhibit IV-5
Comparison of TMS Components Evaluated by Model

						HCM 2000
Ramp Metering	X (user adjusts inputs)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)		X (delay and safety adjustment)	X (capacity adjustments)
Arterial Signal Management	X (user adjusts speed)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)		X	X (capacity running times and control based on various factors)
Signal Coordination with Ramp Metering		X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)		Would need to assess separately and be combined	
Incident Management	X (user defines incident duration reduction and coverage)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)		X (incident duration and fatality reductions)	
Real-Time Traveler Information Systems	X (user input utilization and time savings)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)		X (CMS only, incident delay reduction)	
Electronic Toll Collection	X (user input service times for toll processing types)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)	X		
Advanced Public Transportation Systems (APTS)	X (time savings and ridership/ vehicle trip decreases)	X (user estimates demand impact prior to use of tool)	X (user estimates capacity, travel cost and demand impacts prior to use of tool)			
Bus Rapid Transit (BRT)		X (user estimates impact prior to use of tool)	X (user estimates impacts prior to use of tool)			

The methodology and outputs of SCRITS are as follows. Users are required to supply baseline data into the main Excel worksheet, including the study area definition, as well as travel statistics such as VMT and an estimate of the average weekday daily traffic divided by the hourly capacity (AWDT/C). Users may input estimates or recurring and non-recurring VHT directly and make a choice between SCRITS-generated values or their own directly input values.

The specific "baseline" inputs required from the user for analyses in SCRITS include:

- Year represented in the analysis
- Centerline miles for facilities being analyzed (freeway and/or arterial)
- Proportion of freeway miles with shoulders at least one side
- Weekdays per year
- Weekday VMT for study area facilities being analyzed
- Ratio of AWDT to AADT
- AWDT/Capacity for facilities being analyzed
- Recurring VHT on average weekday for facilities being analyzed (optional – can be estimated by tool)
- Ratio of non-recurring VHT to recurring VHT (optional – can be estimated by tool)
- Average vehicle occupancy
- Cost of time per person-hour
- Area/regional average vehicle trip length (miles)
- Area/regional average vehicle trip time (minutes)
- Area/regional number of weekday daily vehicle-trips
- Average incident duration (minutes)
- Freeway accidents per million VMT
- Percentage of secondary freeway accidents of total accidents
- Arterial accidents per million VMT
- Average cost per accident.

The relationship between the AWDT/C ratio and daily average speed is documented in tables used in the FHWA/National Highway Institute training course "Estimating the Impacts of Urban Transportation Alternatives" (National Highway Institute, 1995). These tables are the basis of the "FwySpeed" and "ArtSpeed" worksheets contained in this application, which are used to calculate recurring VHT. The relationship between the AWDT/C ratio and non-recurring VHT is based on research by Margiotta and Cohen (1998). A ratio of non-recurring VHT to recurring VHT is extracted from another lookup table called "inc_pct", and is then multiplied by the estimate of recurring VHT to derive the non-recurring VHT. The calculation uses the fraction of freeway with shoulders when it derives the weighted average of the ratio between non-recurring and recurring VHT. The SCRITS tool makes extensive use of speed calculations in the baseline worksheet and related estimates of VHT.

An additional lookup table, "emis_fac" stores estimates of grams per mile for three pollutants (CO, NOx, and HC), as well as vehicle operating costs per mile, and fuel consumption per mile. Each five-mile increment of speed has an associated emission factor or operating cost factor. In particular analyses where emissions and operating cost values are used, the calculations are performed by entering a speed value into the lookup table and interpolating emission factors associated with the nearest two speed values.

SCRITS outputs vary by individual analysis, but generally encompass the following:

- Changes in VHT (for most applications)
- Changes in VMT, where applicable
- Changes in emissions (CO, NOx, HC), where applicable
- Changes in vehicle operating costs, where applicable
- Changes in energy consumption, where applicable
- Changes in the number of accidents, where applicable
- Economic benefit and benefit-cost ratio (for most applications).

Surface Transportation Efficiency Analysis Module (STEAM)

STEAM is a transportation/economic impact analysis tool developed by the Federal Highway Administration.[9] It is used for detailed, system-wide analyses of alternative transportation investments. When first introduced in 1997, it was the first FHWA impact analysis product to use outputs directly from the four-step travel demand modeling process.[10] STEAM post-processes the traffic assignment volumes that are generated by the four-step models and derives highway travel speeds that are sensitive to congestion and queuing impacts. STEAM applies consumer surplus theory to estimated user benefits of alternative programs and policies.

The latest version of the model, STEAM 2.0, can perform monetized impact estimates for a wide range of transportation investments and policies, including major capital projects, and pricing and travel demand management (TDM). STEAM provides flexibility in transportation modes, trip purposes, and time periods analyzed. The model has default analysis parameters for seven modes: auto, truck, carpool, local bus, express bus, light rail, and heavy rail. Users can specify different values of time for different travel markets. They are asked to provide "base case" and "improvement case" trip tables for different trip purposes. STEAM can be applied to average weekday traffic or to peak and off-peak traffic with different definitions of the peak periods.

STEAM provides estimates for the following:

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[9] *Overview of most recent version comes from the STEAM 2.0 User Manual found at :*
   http://www.fhwa.dot.gov/steam/20manual.htm

[10] *STEAM 1.0 was developed in 1996 by DeCorla-Souza, Cohen & Bhatt.*

- Benefits and costs to transportation users
- Annualized costs to public agencies
- Effects on total transportation cost
- Changes in accessibility to jobs for residents of defined districts
- Changes in emissions for particular, hydrocarbons, carbon monoxide, and nitrogen oxides
- Changes in energy use
- Changes in noise and other external costs
- Changes in fatal, injury, and property damage only accidents
- Revenue transfers due to toll or fare changes.

STEAM does not estimate the benefits of TMS improvements directly. The user is responsible for estimating the demand impact of an improvement such as a toll facility, and constructing a "build" versus "no build" scenario. This implies that assumptions about TMS improvements must come from the agency employing the analysis or from external evaluation studies or research performed on TMS components. User-defined trip tables by origin-destination zone for both scenarios are then fed into STEAM for analysis. In that sense, STEAM does not differentiate between operational and non-operational improvements explicitly.

Sketch Planning Analysis Spreadsheet Model (SPASM)

SPASM was developed by the FHWA in 1995 to aid planners in compiling economic efficiency and related information needed for comparing cross-modal and demand management strategies.[11]

The application is a precursor to STEAM and, unlike STEAM, it does not use input directly from the four-step travel demand modeling process. SPASM is implemented in Excel worksheets and enables users to evaluate sets of transportation actions at the system and corridor level, including:

- Transit system improvements
- Highway capacity improvements
- HOV improvements
- Auto-use disincentives
- Combinations of the above actions.

SPASM provides estimates of the following:

- Benefits and costs to transportation system users, including travel time and operating and out-of-pocket costs

[11] *SPASM User's Guide; September, 1998.*

- Annualized costs to public agencies
- Effect on total transportation cost
- Change in emissions for hydrocarbons, carbon monoxide, and nitrogen oxides
- Change in energy use.

Additionally, SPASM concerns itself with these effects:

- Discounting of costs and benefits over time
- Congestion-related effects of changes in vehicle miles of travel on speeds during peak and off-peak periods
- Diversion of traffic among parallel highway facilities in a corridor
- Induced (or discouraged) traffic as a result of changes in highway congestion levels
- Effects of speed and cold starts on motor vehicle emissions and fuel consumption
- Benefits to travelers resulting from increased trip-making due to travel time and cost savings.

The user provides estimates of initial effects of the actions on highway capacity, travel costs, and travel demand for five transportation modes that include automobile, truck, carpool, bus, and rail. The SPASM spreadsheet then calculates effects on highway speeds and subsequent changes in highway usage related to these speed effects.

This tool does not calculate benefits of TMS improvements directly, and it has been superseded in sophistication and functionality by STEAM. The same limitations apply to SPASM as for STEAM. The user must make independent assumptions about TMS operational improvements and the related demand impacts before using this tool for analysis. SPASM is appropriate for such planning applications where travel demand model outputs are not available.

IMPACTS

The IMPACTS spreadsheet software was developed in 1996 in tandem with the workshop exercises for the National Highway Institute course "Estimating the Impacts of Urban Transportation Alternatives."[12] It contains seven Excel worksheets that encompass different alternatives: highway expansion, bus system expansion, light rail transit investment, HOV lanes, conversion of an existing facility to a toll facility, employer-based travel demand management, and bicycle lanes. Analysis can be conducted over a single facility or a corridor (provided that the analysis is repeated for each affected facility), and for different markets and travel segments. Separate analyses are needed by mode if the user wishes to evaluate multi-modal improvements.

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[12] *IMPACTS was programmed in Excel by Jim Altenstadter of the Pima Association of Governments; Tucson, Arizona.*

The estimated impacts of the alternatives include:

- Costs of implementation (including capital, operation, and maintenance)
- Benefits (or dis-benefits) accruing to previous "base case" users, including trip time and out-of-pocket costs (e.g., fares, parking fees and tolls)
- Benefits (or disbenefits) accruing to induced (or discouraged) trips
- Savings to highway users due to reduced congestion
- Changes in other highway user costs, such as accident costs and costs for parking
- Revenue transfers due to tolls, fares or parking fees
- Changes in fuel consumption
- Changes in emissions.

The IMPACTS tool include the following procedures. Capital, operating, and maintenance costs are estimated using inputs that include capital costs, midpoint of period when costs are incurred, year of opening, useful life, and discount rate. IMPACTS calculates the benefits (or disbenefits) to toll users, HOV or bicycle lane users that result from bicycle, HOV or transit improvements and from price, toll or transit fare changes. The spreadsheet then estimates effects on congestion delay due to changes in VMT resulting from mode shifts using delay coefficients and average speeds for various ratios of Average Weekday Daily Traffic to Hourly Capacity (AWDT/HC). The change in congestion delay to existing "base case" vehicles is also estimated. The spreadsheet then estimates induced (or discouraged) highway traffic due to changes in congestion delay resulting from VMT or highway capacity changes (beginning with an "un-equilibrated" highway VMT, deriving and applying an equilibrium factor, and concluding with an equilibrated VMT and related speed). Impacts for highway users are estimated in terms of change in consumer surplus. Parameter data, including coefficients and unit costs, are employed in benefit estimation for changes in emissions and energy consumption. In the end, the spreadsheet compares benefits with cost of implementation to derive a benefit-cost ratio, net annual benefit, and net present value.

IMPACTS, like STEAM and SPASM, employs an economics-based framework and produces similar outputs. Like SPASM, it does not take the outputs of other models such as travel demand models as inputs. However, SPASM software can more easily analyze improvements to more than one mode for a single alternative. In terms of analyzing TMS benefits, IMPACTS suffers from the same limitations as the other models. It does not explicitly or directly evaluate operational improvements (except for toll facilities) nor does it have default values for ITS-related costs and benefits.

Highway Economic Requirements System (HERS) Operations Preprocessor

HERS is a computer model designed to estimate the costs, benefits, and national economic implications associated with various highway investments. The HERS model

is used in the Department of Transportation's (DOT) *Status of the Nation's Surface Transportation System – Condition and Performance – Report to Congress (C&P Report)*, which is produced biennially. HERS estimates the benefits to highway users (travel time, operating costs, and safety), to highway agencies (maintenance costs and the residual value of an improvement at the end of the analysis period), and reduction in vehicle emissions. A benefit-cost analysis compares potential improvements. For each funding period, HERS forecasts the condition of each sample section and determines which improvements should be made. The current version of the HERS model considers highway improvements to the pavement (resurfacing and reconstruction) and geometrics (lane widening and additions; shoulder improvements; curve and grade improvements; and access control; and median improvements for urban freeways). The current HERS software structure does not accommodate testing of TMS systems (called operational improvements in HERS). However, a project is currently underway to incorporate these types of improvements into HERS.

An independent Operations Preprocessor was developed for a division of the ITS Joint Program Office.[13] This Preprocessor has been used in limited fashion by the Joint Program Office to provide information outside the reach of HERS, but it has not been validated or implemented as a tool within HERS in its own right.

The Preprocessor uses a simpler strategy than HERS, which includes scheduling operational improvements and keeping track of deployment costs.[14] However, the Preprocessor does not make assessments about user impacts. Instead, it upgrades the base conditions on the FHWA's Highway Performance Monitoring System (HPMS) segments and modifies the HPMS dataset. This modified dataset is input to the main HERS model. In this way, HERS obtains highway system input data with the TMS systems already included. Using this approach, the user compares the user impacts of TMS between two separate runs of HERS: one run with an operationally improved system and another without.

The Operations Preprocessor deviates from HERS in that it considers improvements at the corridor level rather than on isolated segments which is more consistent with TMS evaluation. Corridor-wide v/c ratios are used as the primary triggers for improvements. When an operational improvement is made, capacity is increased to reflect the impact of the improvement to determine the need for future improvements. The assumed capacity increases for each type of strategy are:

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[13] *Information on these tools was gathered through interviews with Herb Weinblatt and Rich Margiotta of Cambridge Systematics, as well as the HERS Preprocessor documentation.*

[14] *Cambridge Systematics constructed the Operations Deployment Scenarios for the Preprocessor, which include: arterial management, freeway management, incident management, and traveler information components, as well as TMC deployment and TMC software upgrade. Scheduling assumptions are made for (1) existing trends and (2) aggressive deployment, stratified for some components by urban area size (> 2 million, 1-2 million, etc.).*

- Signal control – 7.5 percent increase for each increase in level (fixed time to traffic actuated to closed loop to real-time traffic adaptive)
- Signal preemption – no increase
- Incident detection – 5 percent increase
- Incident verification – 5 percent increase
- Incident response – 7.5 percent increase
- CMS – 0.5 percent increase
- Ramp meters – 5 percent increase
- Electronic surveillance and TMC deployment – no increase.

The Operations Preprocessor provides adjustment factors that are applied within the HERS model instead of estimating user impacts directly. The impacts for the available operational improvements are summarized in the sections on detailed methodology.

Highway Capacity Manual (HCM)

The Highway Capacity Manual (HCM) provides techniques for estimating the capacity and level of service for transportation facilities. Although not a tool itself, the document includes worksheets for determining the quality of service and analytical procedures for several other performance measures. The methodologies are generally for traditional roadway, bicycle, pedestrian, and transit projects, however, some operational improvements are available as well. Generally, speed and delay are the performance measures produced for individual system elements and these can be used to estimate impacts for system analysis (by converting to travel times and aggregating the values).

The latest HCM analytical procedures (found in the 2000 HCM) are based on estimates of travel time and delays along segments or at a particular point. A segment is a facility (freeway, urban street, or rural highway) with consistent demand and capacity over its length. A point is a very short portion of the facility where demand or capacity changes abruptly. The segment and point travel times and delays are converted to person-hours and summed to estimate the impacts. Most of the procedures require estimates of hourly demand in each direction and some can be quite complex.

2.2   Ramp Metering

SCRITS

SCRITS does not differentiate between types of ramp metering strategies for estimating benefits. The structure of the analysis includes the assessment of changes in VHT on the freeway, parallel arterial(s), and the metered ramp(s). As inputs, it requires estimates of average speed with and without metering for the freeway and arterial. It recommends reviewing documented speed changes for before-and-after evaluations of actual ramp meter deployments. The delay at the ramp is estimated using a user-inputted average delay per vehicle at the ramp multiplied by the vehicle volume for the time period being analyzed (typically peak period). The change in VHT is the

difference between with and without metering. SCRITS analysis of ramp metering includes time savings and accident savings. It does not estimate emissions, energy, or vehicle operating costs savings.

Inputs for evaluation of ramp metering in SCRITS include:

- "Baseline" inputs identified in Section 3.1
- Percentage of study area freeway section being metered
- Percentage of freeway volume in peak period being analyzed
- Percentage of freeway volume in peak direction
- Average freeway speed without metering (mph)
- Average freeway speed with metering (mph)
- Number of metered ramps in direction analyzed
- Average metered volume per ramp over period
- Average peak period delay per vehicle on ramps (seconds)
- Percentage of arterial volume in peak period being analyzed
- Percentage of arterial volume in peak direction
- Average arterial speed without metering (mph)
- Average arterial speed with metering (mph)
- Percent reduction in accidents.

STEAM and SPASM

These tools do not estimate the benefits of ramp metering directly. The user is responsible for estimating the demand, capacity, and/or travel cost impacts prior to use of the tool.

HERS Preprocessor

The HERS Operations Preprocessor uses the following impacts for ramp metering:

- *Congestion/delay*: New delay = 0.16 hours per 1000 VMT – 0.13 (original delay)
- *Safety*: -3 percent number of injuries and PDO accidents.

IMPACTS

This tool does not estimate the benefits of ramp metering.

HCM

The effects of a ramp metering strategy can be evaluated by modifying the ramp roadway capacities to reflect the desired metering rate. The methodology does not take into account the effect on adjacent arterials. Ramp metering impacts are computed based on the following steps: manually adjust segment demands to simulate the effect

of demand diversion onto adjacent facilities; calculate segment capacity using HCM methods and adjust capacity to reflect ramp metering impacts; generate an adjusted demand to capacity matrix by segment and time interval and identify whether under-saturated or oversaturated; use the appropriate methodology for under-saturated and oversaturated conditions to calculate queues and estimate speeds and densities on each segment; conduct bottleneck analysis; and aggregate individual segment impacts for each time interval (VMT, VHT, VHD, and travel time).

The HCM requires the following input data for a freeway analysis:

- Geometric data for each segment
  Length
  Mainline number of lanes
  Mainline average lane width (feet)
  Mainline lateral clearance (feet)
  Terrain (level, rolling, or mountainous)
  Ramp number of lanes
  Ramp acceleration or deceleration lane length (feet)
- Traffic characteristics data for each segment
  Mainline free-flow speeds
  Vehicle occupancy
  Percent trucks and buses
  Percent recreational vehicles
  Driver population (commuter or recreational)
  Ramp free-flow speeds (mph)
- Demand data for each segment
  Mainline entry demand for each time interval
  On-ramp demands for each time interval
  Off-ramp demands for each time interval
  Weaving demand on weaving segments.

2.3   Arterial Signal Management

SCRITS

SCRITS does not differentiate between types of traffic signalization strategies for estimating benefits. The analysis is based on assumptions in average system speed with and without the TMS signalization application. The VMT and VHT data in the baseline worksheet provides an estimate of existing average system speed. The user must input an estimated percentage increase in speed, found in sources such as signal system before-and-after evaluation studies as well as the Institute of Transportation Engineers'

document "Strategies for Alleviating Traffic Congestion."[15] Changes in VHT are calculated based on the VMT divided by the average speeds with and without the TMS improvements. The estimated change in the number of stops can also be incorporated into the calculation of benefits, but it requires the user to estimate the number of stops per VMT and the percentage change in number of stops as a result of the system. The change in the number stops is included in the estimate of emission benefits by assuming the elimination of deceleration/acceleration cycles, each of which is assumed to generate a fixed quantity of emissions. SCRITS produces estimates of time savings, accident savings, fuel cost savings, and changes in emissions.

SCRITS requires the following inputs for the evaluation of signals:

- "Baseline" inputs identified in Section 3.1
- Percent improvement in average speed expected, based on evaluation data
- Current number of stops per VMT
- Percent reduction in stops expected.

STEAM and SPASM

These tools do not estimate the benefits of signal systems directly. The user is responsible for estimating the demand, capacity, or travel cost impacts prior to use of the tool.

IMPACTS

This tool does not estimate the benefits of signal systems.

HERS Preprocessor

Signal control in the HERS Operational Preprocessor is based upon upgrade level (fixed time to traffic actuated to closed loop to real-time traffic adaptive). The impacts of the different levels of signal control are directly considered in HERS delay equations through a signal density factor, V/C ratio, and travel rate.

HCM

The HCM includes a methodology for analyzing the capacity and LOS of isolated signalized intersections for lane groups and intersection approaches. The methodology considers flow rates at the intersection, signalization, geometric characteristics, and the

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[15] This document provides a consolidated assessment of increases in average speed based on the existing level of signal coordination and proposed level of signal coordination/system sophistication. It also provides data on typical changes in the number of stops.

delay or LOS that result. Worksheets are available in the HCM to guide the user through the steps for computing the capacity and LOS for signalized intersections.

The required input data for analysis of isolated signals in HCM includes:

- Geometric conditions for each lane group
    Area type
    Number of lanes
    Average lane width (feet)
    Grade (percent)
    Existence of exclusive left-turn or right-turn lanes
    Length of storage bay, left-turn or right-turn lane
    Parking
- Traffic conditions for each lane group
    Demand volume by movement
    Base saturation flow rate
    Peak hour factor
    Percent heavy vehicles
    Approach pedestrian flow rate
    Local buses stopping at intersection (buses/hour)
    Parking activity (maneuvers/hour)
    Arrival type
    Proportion of vehicles arriving on green
    Approach speed (mph)
- Signalization conditions
    Cycle length (seconds)
    Green time (seconds)
    Yellow-plus-all-red-change-and-clearance interval (seconds)
    Actuated or pre-timed operation
    Pedestrian push button
    Minimum pedestrian green (seconds)
    Phase plan
    Analysis period (hours).

For coordinated signals, two components are included in the travel time estimate: running time and control delay at the signalized intersections. Running time is based on the street's classification, length, and free-flow speed. The running time is found by using a table in the HCM. The control delay is a function of uniform delay, incremental delay, initial queue delay, and a progression adjustment factor. Worksheets are available to assist the user in applying the methodology.

Inputs to estimate the delay values for coordinated signal systems include:

- V/C for the lane group
- Cycle length (seconds)

- Capacity of the lane group (vehicles per hour)
- Effective green time for lane group (seconds)
- Duration of analysis period (hours)
- Incremental delay adjustment for actuated control
- Incremental delay adjustment for the filtering or metering by upstream signals.

2.4 Signal Coordination with Ramp Metering

The benefit-cost tools reviewed and the HCM do not estimate the impacts of signal coordination with ramp metering. As described in Deliverable 2a, IDAS allows for the combination of these components. However, IDAS has the benefit of reassigning the traffic based on the impacts of the components. Analysis of these systems could also be accomplished through the use of simulation tools as was done in the Caltrans TMS Financial Plan.

2.5 Incident Management

SCRITS

SCRITS does not estimate the benefits of incident management as a single process. Instead, the model considers separately the impact of detection and closed-circuit television (CCTV).

Detection. The "detection" worksheet examines the benefits of installing inductive loops or other detection devices to enable gauging of real-time characteristics of traffic flow. It does not include dissemination of information collected to the public. The main benefit of detection, as defined in this worksheet, is potential reduction in incident duration. The user must provide an estimate of the reduction in average incident duration and the coverage of detection devices across the freeway (it is assumed that detectors are placed at half mile intervals, typical of most freeway systems). SCRITS produces annual savings in time costs and vehicle operating costs as benefits.

SCRITS requires the following inputs for evaluating the impacts of detection on incident management:

- "Baseline" inputs identified in Section 3.1
- Percent detection coverage of freeway system before improvement
- Percent detection coverage of freeway system after improvement
- Estimated reduction in average incident duration (minutes)
- Change in VMT per weekday.

CCTV. SCRITS does not evaluate the full-range of incident response and management. However, it does include an estimate of the reduction in average incident duration that may result from having CCTV available to conduct visual observation of incidents. The

non-recurring VHT benefits are estimated on the basis of reductions in average incident duration. The user enters the reduction factor and the model multiplies the factor by an estimate of non-recurring VHT in the "baseline" worksheet and the CCTV coverage percentage. Benefits estimated by SCRITS for CCTV include annual time savings and vehicle operating costs. In addition, SCRITS assumes CMS are also used for incident management.

SCRITS requires the following inputs for evaluating the impacts of CCTV on incident management:

- "Baseline" inputs identified in Section 3.1
- Percent CCTV coverage of freeway system before improvement
- Percent CCTV coverage of freeway system after improvement
- Estimated reduction in average incident duration (min.)
- Savings in VMT per weekday.

STEAM and SPASM

These tools do not estimate the benefits of incident management directly. The user is responsible for estimating the demand, capacity, and/or travel cost impacts prior to use of the tool.

HERS Preprocessor

The HERS Operations Preprocessor uses the following impacts for the analysis of incident detection and verification:

- Incident duration reduced 4.5 percent
- *Safety*: -5 percent fatalities, with reduced number of fatalities added to number of injuries.

The HERS Operations Preprocessor uses separate impacts for incident response and management (e.g., on-call service patrols and TMC integration or coordination):

- Incident duration reduced 25 percent
- *Safety*: -10 percent fatalities, with reduced number of fatalities added to number of injuries.

When incident detection, verification, response and management are combined, the HERS Operations Preprocessor uses a different set of impacts:

- Incident duration reduced by 4.5 percent and then 25 percent
- *Safety*: -10 percent fatalities, with reduced number of fatalities added to number of injuries.

IMPACTS and HCM

The above tools do not estimate the benefits of incident management systems.

2.6   Real-Time Traveler Information Systems

SCRITS

SCRITS does not evaluate real-time traveler information as a single TMS process. Instead, the model allows the user to analyze an number of different components: highway advisory radio (HAR), changeable message signs (CMS), web-based traveler information, and kiosks. These benefits should not be additive if multiple traveler information systems are deployed.

HAR. SCRITS requires assumptions about average time savings if a motorist alters a route as a result of information provided by HAR. The user must supply information about the frequency of HAR use consistent with the agency's operational philosophy or anticipated operation of this service. Sensitivity analysis is warranted to analyze a range of assumptions. In addition, the analyst must make an estimate for the average or typical condition that may surround an incident, since this is related to the likelihood that a diversion would be made. The methodology is based upon multiplying various utilization factors by the average volume of travelers in the HAR-covered area. SCRITS estimates time and accident savings for this component. The impact of diversion on emissions and vehicle operating costs is left out of the analysis, since diversion could decrease VHT while increasing VMT.

SCRITS requires the following inputs for the evaluation of HAR:

- "Baseline" inputs identified in Section 3.1
- Number of transmitters to be installed
- Average volume (VPH) through HAR unit reception area
- Time (hours) transmitter active for each incident
- Number of times/day each transmitter activated
- Percent of drivers that tune to broadcast
- Percent of drivers hearing broadcast that save time
- Amount of time (minutes) saved by each vehicle saving time
- Percent reduction in secondary accidents (from improved warning).

CMS. The approach for CMS is similar to that of HAR as they both provide information to travelers en-route. The analysis is based on the percentage of drivers who may benefit from diversion and their estimated time savings taking into consideration that traveler response to CMS varies widely according to context (severity of the congestion, availability of alternate routes, agency policy for using the CMS, etc.). The

methodology assumes that CMS are used for incident management. SCRITS produces time and accident savings only for CMS.

SCRITS requires the following inputs for the evaluation of CMS:

- "Baseline" inputs identified in Section 3.1
- Number of changeable message signs to be installed at strategic points on freeway
- Average volume (VPH) past sign
- Number of times per day each sign provides incident information
- Time (hours) sign active for each incident
- Percent of drivers (vehicles) passing sign that save time
- Amount of time (minutes) saved by each vehicle passing sign.

Web-based traveler information. The SCRITS methodology for measuring the benefits of real-time traveler information via the Internet is based on market penetration (travelers likely to check the information before they leave) and the time they may save through diversion or trip time changes. Unfortunately, little is known about how much time is actually saved by most travelers through diversion and since SCRITS is based on daily analysis, the user must assume a time savings associated with altering their departure time within the time savings input value. Time savings is the only benefit measured for Internet service in SCRITS.

SCRITS requires the following inputs for the evaluation of web-based traveler information systems:

- "Baseline" inputs identified in Section 3.1
- Percentage of trips for which internet access is available
- Of those, number of persons looking at information as they depart
- Of those looking at information, percentage that may be able to save time
- Amount of time (minutes) saved by each person saving time.

Kiosks. The methodology for kiosks in SCRITS is similar to Internet services in that they only address a specific portion of travelers (those who have access). It is based on market penetration and time they may be able to save. The benefit measure is time savings. User assumptions must be made about number of kiosks, number of trips made in vicinity of kiosk location, number of people who obtain information from the kiosk, number of people who will actually save time, and average time saved by each person.

STEAM and SPASM

These tools do not estimate the benefits of real-time traveler information systems directly. The user is responsible for estimating the demand, capacity, and travel cost impacts prior to use of the tool.

HERS Preprocessor

CMS are included within the HERS Preprocessor for both freeway and arterial facilities. The HERS Preprocessor assumes that for both freeways and arterials CMS reduce incident-related delays by 0.5 percent.

IMPACTS and HCM

These tools do not estimate the benefits of traveler information systems.

2.7   Electronic Toll Collection

SCRITS

One of the benefits of electronic toll collection (ETC) is to internal agency operation (reduction on toll collectors, automated accounting systems, etc.) and this can be included in the cost calculation within SCRITS. Since SCRITS is a sketch-planning spreadsheet-based tool, it cannot capture the queuing and the resulting impact on vehicle delay due to ETC. It estimates the time savings due to processing time only. Savings in vehicle-hours are computed using the difference between the total processing times with and without electronic toll collection.

Inputs for evaluation of ETC in SCRITS:

- "Baseline" inputs identified in Section 3.1
- Total average weekday daily volume through toll plaza
- Current percent volume through current exact change lanes (before ETC)
- Current percent volume through current regular lanes (before ETC)
- Current percent volume through current pass lanes (before ETC)
- Percent volume through electronic toll lanes (with ETC)
- Percent volume through exact change lanes (with ETC)
- Percent volume through regular lanes (with ETC)
- Percent volume through pass lanes (with ETC)
- Average service times (seconds - includes slowing at plaza) for electronic toll lanes
- Average service times (seconds - includes slowing at plaza) for exact change lanes

- Average service times (seconds - includes slowing at plaza) for regular lanes
- Average service times (seconds - includes slowing at plaza) for other lanes.

STEAM and SPASM

These tools do not estimate the benefits of ETC directly. The user is responsible for estimating the demand, capacity, and travel cost impacts prior to use of the tool.

HERS Preprocessor

The HERS Preprocessor does not consider this component.

IMPACTS

The only TMS improvement available for analysis in IMPACTS is Toll Collection/ Congestion Pricing. Using the various inputs provided by the user and several rate tables within the spreadsheet, IMPACTS computes mobility and congestion benefits, accident savings, vehicle operating costs, parking costs, emissions impacts (HC, CO, NOx), fuel consumption, and revenue transfer.

IMPACTS needs the following inputs to evaluate ETC:

- Modal split (percent of ADT) for each mode
- Average trip length by mode (miles)
- Total daily VMT by mode
- Average daily traffic (vehicles)
- Auto and bus occupancy
- Daily parking cost
- Weekday traffic volume to capacity ratio
- Number of auto person trips without toll
- Number of auto person trips with toll
- Change in average in-vehicle travel time (minutes/trip)
- Change in out-of-pocket cost due to toll
- Fraction of eliminated auto person trips that shift to bus
- Average auto occupancy after toll
- Passenger car equivalents for trucks and buses
- Elasticity (VMT/travel time).

HCM

HCM does not estimate the benefits of toll facilities.

2.8 Advanced Public Transportation Systems (APTS)

SCRITS

SCRITS considers separately two components of APTS: automatic vehicle location (AVL) and transit signal priority.

AVL. SCRITS accommodates an evaluation of AVL systems for buses, under the assumption that information on bus location is available to travelers through cable TV, the internet, or related media, and that they can use this information to reduce their wait time at bus stops. The reduction in traveler waiting time at the bus stop is the only benefit analyzed in the "BusAVL" worksheet.

SCRITS requires the following inputs for the evaluation of AVL:

- "Baseline" inputs identified in Section 3.1
- Current average wait time per passenger (minutes)
- Average wait time with AVL system (minutes)
- Average number of weekday daily boardings
- Average number of daily boardings, full week
- Percent of passengers that use the information.

Signal priority. SCRITS provides an order-of-magnitude estimate of time savings for buses that are given priority and additional delay for side-street traffic. The methodology allows for an elasticity to estimate potential increases in ridership and decreases in vehicle trips.

SCRITS requires the following inputs for the evaluation of transit signal priority:

- "Baseline" inputs identified in Section 3.1
- Miles on which priority treatment is implemented
- Number of buses per weekday on priority routes
- Current average bus speed on arterials (mph)
- Percentage of bus travel time attributable to signal delay
- Estimated percent reduction in signal delay from pre-emption
- Number of daily bus passengers on affected routes
- Average bus passenger trip length (miles)
- Elasticity of demand with respect to bus speed
- Daily vehicle trips on corridor served by bus routes
- Weekday daily volume of cross street traffic for entire route
- Percentage of cross street traffic that incurs pre-emption delay
- Average delay time per pre-empted vehicle (seconds) for cross street traffic.

STEAM and SPASM

These tools do not estimate the benefits of APTS directly. The user is responsible for estimating the demand, capacity, and/or travel cost impacts prior to use of the tool.

HERS Preprocessor

The Preprocessor does not consider APTS components.

IMPACTS and HCM

These tools do not estimate the benefits of any transit TMS improvements.

2.9   Bus Rapid Transit (BRT)

SCRITS

SCRITS considers the impact of transit signal priority (as described in Section 3.8), but it does not consider other improvements made as part of implementing bus rapid transit, such as adding exclusive bus lanes, incorporating pre-paid or electronic fare payment, or limiting the number of bus stops. SCRITS could estimate the travel time savings associated with signal priority, but the user would have to estimate other travel time savings outside the model.

STEAM and SPASM

These tools do not estimate the benefits of bus rapid transit directly. The user is responsible for estimating the demand and travel time impacts prior to use of the tool.

HERS Preprocessor

The Preprocessor does not consider bus rapid transit.

IMPACTS and HCM

These tools do not estimate the benefits of bus rapid transit.

3.0   RECENT RESEARCH AND FINDINGS

This section provides an overview of related research conducted by California PATH. PATH is a multi-disciplinary research program administered by the Institute of Transportation Studies (ITS) at the University of California at Berkeley (UCB) in collaboration with Caltrans. Over the past few years, Caltrans has sponsored PATH research related to a number of the TMS improvements considered for inclusion in the

most recent Cal-B/C update. The next few sections describe relevant research organized by TMS improvement type.

A short section is also dedicated to a description of a recent Caltrans' study of recurrent and non-recurrent congestion. One of the primary benefits of incident management is a reduction in travel time delays associated with incidents. These delays are often called non-recurrent congestion. A number of other TMS improvements, such as ramp metering and traveler information, also have the potential to reduce non-recurrent congestion. The Cal-B/C model currently captures travel time delays associated with average or recurring conditions. Incorporating an analysis of non-recurrent congestion may be needed in the Cal-B/C update in order to evaluate incident management improvements.

FHWA maintains a database of benefits and costs associated with TMS implementation. IDAS also has an ITS library of benefits and costs. As described in Deliverable 2a, these two sources are updated regularly and reflect revisions to each other. In addition, an extensive review of the ITS benefits literature was conducted as part of developing the Caltrans TMS Financial Plan. IDAS is currently being revised and will incorporate this additional research into the ITS Library.

The appendix presents empirical data from the IDAS ITS Library, which may be useful in developing parameters for the Cal-B/C update. The library is intended to provide users with information on direct benefits experienced or estimated to have occurred with the deployment of TMS components. Several performance measures are documented in the library:

- Travel time, speed, and delay
- Throughput, capacity, and vehicle stops
- Change mode
- Change time of day
- Change route
- Safety
- Customer satisfaction
- Emissions
- Energy
- Costs
- Efficiency.

3.1 Ramp Metering

Assessing the Benefits and Costs of ITS: Ramp Meters

A study was conducted by Kang and Gillen at California PATH to provide empirical information on the value of ramp metering. The benefits and costs were based on assumptions, simulation, and travel pattern data for an isolated, single traffic-

responsive ramp meter. The user benefits were estimated in terms of travel time savings, fuel consumption, and vehicle operation cost savings. Emissions were included as a cost item.

Several assumptions were made in the analysis:

- 3-lane freeway and 1-lane ramp
- 1-mile section length upstream of on-ramp merge
- 4 second ramp rate
- Parameter values for cell transmission model: q_{max} = 1,800 vph; u = 60 mph; w = 15 mph; and k_j = 210 vpm
- Maximum queue = 40 vehicles (with queue control)
- Travel demand data from I-880 freeway database (Alameda, CA) in 1993, increased by 3 percent per year for the base year (1999)
- Fuel consumption: average speed = 60 mph; average fuel consumption = 25 mpg; and cost per gallon = $1.10 (1995 dollars)
- Passenger travel time savings: vehicle split = 94.76 percent autos, 5.11 percent trucks, 0.13 percent buses; vehicle occupancy = 1.8 for autos, 1.1 for trucks, and 20 for buses; value of time = $12.75 per hour for autos and buses, and $33.41 per hour for trucks
- Emissions: year 2000; 75 degrees temperature; autos and trucks catalyst gasoline vehicles and buses are diesel; unit costs per kg– HC = $1.28, CO = 0.0063, and NOx = 1.28
- 5-percent discount rate.

The effect of freeway and ramp excess demand was estimated using a cell transmission model. As excess demand grows, it is estimated that ramp metering saves more travel time. Daily travel delay reductions were computed by doubling the morning peak estimates, and annual delay was calculated by multiplying the daily by 261 (number of workdays). The average fuel cost savings was computed by dividing the average travel speed by average fuel consumption and multiplying that value by the total vehicle time savings and the unit price of gasoline. Passenger time savings were calculated by multiplying the total delay savings by vehicle occupancy factor and the value of time savings. Emissions (HC, CO, NOx) were estimated based on emission rates by travel speed from EMFAC7G, vehicle volumes, and the per-unit costs of pollutant.

The Ramp Metering Benefit-Cost Analysis Model (spreadsheet) was developed as part of this effort. The model requires the following inputs:

- Traffic inputs
    Number of freeway lanes
    Number of ramp lanes
    Length of freeway upstream to the merge point
    Start and end time of the morning and afternoon peak periods
    Period of time that meter rate is updated

Period of time that the travel demand on freeway and ramp is updated

Travel demand on freeway and ramp for each interval update and time period

Free-flow speed on freeway

Wave speed (speed that queue propagates backward)

Critical density (vehicles/mile/lane) – number of vehicles on freeway at capacity

Jam density (vehicles/mile/lane) – maximum number of vehicles that can be present on the freeway

Capacity (vehicles/hour/lane)

Reduced capacity (percent) - capacity reduction downstream to the merge cell at queue present

Maximum ramp queue (vehicles/lane)

Life time of ramp (year) – model assumes 10 years

Annual increase rate of freeway and ramp demand (percent)

Change in freeway and ramp demand (percent) – for sensitivity analysis

- Fuel and travel time inputs

  Average travel speed (mph)

  Average fuel consumption (miles/gallon)

  Fuel cost ($/gallon)

  Ratio of vehicles (autos, trucks, and buses)

  Average vehicle occupancy for each mode

- Emissions inputs

  MVE17G emission factors (grams/mile)

  Conversion factor for ROG to HC

  Idle emission rates (grams/minute)

  Unit costs by pollutant ($/kg)

- Cost inputs

  Construction costs

  Operations and maintenance costs

  Discount ratio.

Outputs from the Ramp Metering Benefit-Cost Analysis Model include:

- Travel time on freeway and travel delay on ramps by time period and daily (vehicle-hours)
- Annual travel delay reduction (vehicle-hours)
- Emissions by time period and daily (kg)
- Annual estimates of emission change (kg)
- Annual fuel consumption reduction
- Annual passenger time savings
- Estimates of annual vehicle emissions change
- Annual benefit stream
- Annual cost stream
- Annual net benefit

- Benefit cost ratio
- Internal rate of return (IRR).

Bay Area Simulation and Ramp Metering Study

This research project involved testing the Paramics simulation model using data for the morning peak on I-680 southbound between I-580 in Pleasanton and SR 237 in San Jose. One of the scenarios simulated was ramp metering. The scenario assumed all 14 on-ramps were metered with a local traffic-responsive ramp metering strategy. The metering rate was determined based on the average lane occupancy on the freeway upstream and varied between a maximum of 900 vph (when mainline occupancy was below 15 percent) and a minimum of 180 vph (when mainline occupancy was over 25 percent).

Both queue control and no queue control scenarios were run. The queue control scenario resulted in a freeway mainline average speed increase from 39 mph to 43 mph (10.9 percent improvement). In the scenario without queue control, the freeway mainline speed increased from 39 mph to 53 mph (37.4 percent improvement).

3.2   Arterial Signal Management

Improved Vehicle-Actuated Traffic Signal Control

Over the past few years, PATH has been researching ways to improve vehicle-actuated traffic signal control with the goals of reducing delay and improving safety. One of the methods is the adoption of wide-area vehicle detectors to monitor vehicles along an entire intersection approach. This study presents the results of three simulation scenarios using a wide-area controller. The greatest benefits were realized at intersections experiencing near-saturation conditions. In these cases, the controller reduced delay by up to 50 percent. The inputs to the simulation scenarios included the number of approaches, number of lanes, free-flow speed (mph), demand (vphpl), and control strategy.

TMS Benefits: The Case of Traffic Signal Control Systems

Using the TRANSYT[16] model to estimate the benefits optimizing coordinated signal systems for 163 projects and 6701 signalized intersections,[17] PATH researchers found a 7.7-percent reduction in travel time, 13.8-percent reduction in delays, 12.5-percent reduction in stops, and 7.8-percent reduction in fuel consumption. Floating car field

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[16] *TRANSYT-7F is a macroscopic deterministic computer model which simulates travel conditions and estimates degree of saturation, travel times, delay, number of stops, fuel consumption, queue lengths, and other performance measures.*

[17] *Real-world results from the California Fuel Efficient Traffic Signal Management (FETSIM) Program over 11 years (1983-1993).*

studies were also conducted on a few of the routes and obtained 7.4-percent reduction in travel time, 16.5-percent reduction in delay, and 17-percent reduction in stops.

Floating car studies were obtained for 76 projects in California and showed that signal coordination reduced travel time by 11.4 percent, delay by 24.9 percent, and number of stops by 27 percent. The majority of benefits are for through traffic with signal spacing up to 0.5 mile and moderate to heavy traffic volumes (V/C > 0.6). The researchers noted that disbenefits to cross streets should be assessed.

3.3   Signal Coordination with Ramp Metering

No PATH research was available for this TMS component.

3.4   Incident Management

Freeway Service Patrol Evaluation

This study involved a comprehensive before and after evaluation of the Freeway Service Patrol FSP program for a 9-mile section of freeway in the San Francisco Bay Area. Field data were collected including incident observations, travel times from instrumented vehicles, and speeds and flows from loop detectors. Database procedures were developed to process the data and included representation of the freeway operating conditions for the freeway segment. Variability in incident occurrence and duration were mostly a result of the type of incident, time of day, day of the week, presence of shoulders, and weather conditions.

Incident information including type, location, severity, assist type, and duration and vehicle travel times were obtained from probe vehicle observations at 7-minute headways. Speeds, flows, and occupancies were collected using 1/3-mile spaced loop detectors on the freeways and ramps. Additional information was obtained from the CHP CAD system, FSP records, and tow truck company logs.

The measures of effectiveness selected for the study included delay, fuel consumption, emissions, and incident duration. Incident-specific delay was estimated from the difference in average travel speeds under normal and incident conditions from loop detector data and instrumented vehicles. Delay was calculated for each time slice (one to five minutes) and each segment upstream influenced by the incident and summed:

$$D_{ki} = L_k \left(\frac{\Delta T}{60}\right) Q_{ki} \left(\frac{1}{V_{ki}} - \frac{1}{V_{kif}}\right) \quad for\ 0 < V_{ki} < V_{kif}$$

$$D_{ki} = Q_{ki} \left(\frac{\Delta T}{60}\right)^2 \quad for\ V_{ki} = 0$$

where: D_{ki} = incident delay on segment k during time slice i (veh-hr)

Q_{ki} = traffic volume on segment k during time slice i (veh-hr)
T = length of time slice (min)
L_k = length of freeway segment (miles)
V_{ki} = average travel speed on segment k during time slice i (mph)
V_{kif} = average travel speed under incident free traffic conditions (mph)

Fuel consumption was estimated for each freeway segment affected by an incident based on a method derived by Lindley:[18]

$$F_{LT} = L\left(\frac{\Delta T}{60}\right) Q_{LT}\left(\frac{0.00657}{1000} + \frac{0.20319}{1000 V_{LT}}\right)$$

where: F_{LT} = fuel consumption on freeway section of length L during time period T (gal)

Emission impacts (HC, CO, and NOx) were estimated using EMFAC7 factors using the following equation:

$$E_{LTn} = L\left(\frac{T}{60}\right) Q_{LT}\, e_{VLTn}$$

where: n = air pollutant (HC, CO, NOx)
E_n = emissions on section L during time T for pollutant n (grams)
e_{VLTn} = emission factor for average speed V_{LT} for pollutant n (grams/mile)

Vehicle assisted motorists also realized time savings due to faster response time. Field observations suggested that the average time savings were 16.5 minutes for FSP and 12.6 minutes for accidents. The savings that assisted motorists experienced were not included in the B/C analysis.

Exhibit IV-6 presents the estimated savings per incident from this study.

Exhibit IV-6
Savings Per Incident from FSP

	Savings per Incident
	0%
	-15%
	-33%
	-25%
	-2%

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[18] *Lindley, J.A., Development of Fuel Consumption and Vehicle Emissions Relationships for Congested Freeway Flow Conditions, Final Report, FHWA/RD-88-205, 1988.*

The same methodologies and types of data were used for an evaluation of the FSP in Los Angeles.

3.5   Real-Time Traveler Information Systems

TravInfo Evaluation: A Study of Transit Information Callers

This document presents findings from a survey of TravInfo (San Francisco Bay Area) Traveler Advisory Telephone System (TATS) callers. The purpose of the survey was to measure the effectiveness of TravInfo in changing travel behavior and assess perceived benefits to users of the service. Of the participants who made the trip after calling TATS (40 percent) for transit information, 41.6 percent modified their plans. 12.4 percent changed both departure time and route, 19.5 percent changed departure time only, and 9.7 percent changed route only. For those who called for traffic information, 4.8 percent changed departure time and route, 10.5 percent changed departure time only, and 27.6 percent changed route only. Mode shift (1 percent) and trip cancellation (3.8 percent) were fairly insignificant. 21.5 percent of transit callers and 35.8 percent of traffic callers believe TATS saved them time.

3.6   Electronic Toll Collection (ETC)

Assessing the Benefits and Costs of TMS Projects: ETC

This study involved an evaluation of the benefits and costs of the Carquinez Bridge electronic toll collection project in the San Francisco Bay Area. The basic information for the study included costs of the existing (before) toll service and ETC, traffic data, toll transactions, and accident information. The study considered several benefits: cost savings (operating and maintenance costs of toll facility, fuel consumption, and vehicle operation); travel time savings; safety improvements (fatality and injury, and property damage); emissions; and other benefits (data quality and quantity, convenience, enhanced facility, and other induced effects such as interest from prepaid accounts). The safety model used was not statistically significant, therefore, safety benefits were not included in the analysis.

The study used the following general assumptions:

- Traffic volume on bridge expected to grow by 3 percent per year
- ETC market share: 6 percent in FY 97/98, 15 percent in FY 98/99, and 5 percent per year after up to 50 percent
- Transaction times: cash = 6 seconds, ticket = 4.5 seconds, ETC = 2.4 seconds
- Normal travel speed = 55 mph
- Design configuration: 0.2 miles on ramps prior to or leading from the toll plaza, total distance on both sides of toll plaza is 0.4 miles

- No induced demand.

Cost savings to the toll agency result from reductions in costs for toll collection service, accounting services, cash handling, equipment replacement/maintenance, lost revenue to system failures, and interest revenues. Annual PY cost was calculated using the following equation:

$$PY_{Sn} = \frac{\left(\dfrac{ETC_n}{ETC_{Cap}} \right)}{U_{PY}}$$

where: PY_{Sn} = annual PY reduction in year n
ETC_n = total ETC transactions in year n
ETC_{Cap} = capacity of ETC lane equals 1,500 (3,600/2.4) transactions per hour
U_{PY} = hours per year, assumed to be 1,768 by Caltrans

The estimation of user costs was based on the following assumptions:

- Average use rate of ETC accounts is 160 per ETC account per year
- Average tag per account is 1.35
- 64 percent of accounts established with check or cash and 36 percent with credit cards
- Average balance is $48.80 for case or check accounts and $19.52 for credit card accounts (1995 dollars).

The number of ETC transactions was estimated by multiplying the projected annual toll transactions by the percentage of ETC transactions. The number of ETC accounts was estimated for cash/check and credit and balances computed. Total balance was calculated by summing the balance of cash/check and credit card accounts. Annual interest revenue was then computed using the total balance and the interest rate.

Operating cost savings for users was captured in fuel cost reductions. Assumptions for the fuel savings estimate included:

- Average travel speed of 55 mph
- Average fuel consumption of 25 miles per gallon
- Vehicle deceleration and acceleration with an average speed of 27.5 mph
- Cost per gallon of $1.10 (1995 dollars).

The fuel savings were calculated by dividing the average travel speed by average fuel consumption. Then total vehicle time savings from the use of ETC were calculated and divided by the hourly gasoline consumption. Time savings were based on annual traffic volumes, annual ticket and cash transactions, and annual ETC usage projections.

Travel time savings was estimated by multiplying the total vehicle time savings by vehicle occupancy (VOC) weighting factor. The VOC factors were based on: mode split of 94.76 percent autos, 5.11 percent trucks, and 0.13 percent buses; and AVO of 1.8 for autos, 1.1 for trucks, and 20 for buses. The time savings was calculated based on the following steps:

1.   Projection of annual traffic volume

$TV_n = TV_{(n-1)} * (1+i_{TV})$

where: TV_n = annual traffic volume in year n
        $TV_{(n-1)}$ = annual traffic volume in year prior to year n
        i_{TV} = average annual traffic increase rate

2.   Projection on annual ticket and cash transactions

$Ticket_n = TV_n * i_{ticket}$
$Cash_n = TV_n * i_{cash}$

where: i =percent of transactions, assumed to be 17 and 83 percent respectively

3.   Projection of annual ETC usage

$ETC_n = TV_n * i_{ETC\_n}$

where: ETC_n = annual ETC usage in year n
        i_{ETC_n} = ETC usage rate as a percent of total traffic volume in year n

4.   Estimation of ETC transactions changing from ticket or cash

$ETC_{ticket\_n} = Ticket_n * i_{ETC\_ticket}$
$ETC_{cash\_n} = ETC_n - ETC_{ticket\_n}$

5.   Estimation of toll transaction time savings (in hours) resulting from changes in ticket and cash to ETC payments

$$T_{m\_etc} = \frac{1}{3600}*[ETC_{ticket\_n}*(4.5-2.4)+ETC_{cash\_n}*(10-2.4)]$$

6.   Time savings estimate from eliminating deceleration and acceleration

$T_{a\_1} = ETC_n * [(D_a/V_d + D_1/V_a) - (D_a + D_1)/V]/3600$

where: T_a = time for approaching toll plaza (where vehicle begins to decelerate and where vehicle stops)
        T_1 = time for leaving toll plaza (when leaves toll and reaches normal speed)

T = time for each vehicle traveling between points where lanes are split and merged at normal speed
D = distances on ramps prior to (D_a) or leading from (D_1) toll plaza
V = average travel speeds (V – normal speed, V_a – acceleration, V_d - deceleration)

7.   Calculate total time savings (in hours). For the study, H and Q were not included due to limitations for field data collection.

$$TS = T_{a\_1} + T_{m\_etc} + H + Q$$

where: H = total headway in hours, product of average headway per vehicle and total vehicles
Q = total queuing delay in hours, derived by multiplying average reduction in queuing time per vehicle by total vehicles

8.   Calculation of VOC weighting factor (F_t) with value of time

$$F_t = (U_{t\_auto} * VOC_{auto} * i_{auto} + U_{t\_truck} * VOC_{truck} * i_{truck} + U_{t\_bus} * VOC_{bus} * i_{bus})$$

where: U_t = units of time ($12.75 per hour for autos and buses and $33.41 for trucks)

9.   Weighted time savings computed by multiplying total time savings by VOC factor.

Vehicle emissions benefits were estimated using emission rates, fuel reduction, and time savings from ETC. The equations used for calculating emissions (NOx, HC, CO) were:

$$TE_{NOx} = E_{NOx\_a} * G$$
$$TE_{HC} = (E_{HC\_i} * T) + (E_{HC\_a} * G)$$
$$TE_{CO} = (E_{CO\_i} * T) + (E_{CO\_a} * G)$$

where: E_a = emission rates for acceleration events
E_i = emission rates for idling events
G = total annual fuel reduction
T = total annual time savings of toll transactions

The Electronic Toll Collection Cost/Benefit Model was developed as an Excel spreadsheet to implement the methodology described above. A user's manual accompanies the model.

3.7 Advanced Public Transportation Systems (APTS)

Bus Operations in Santa Clara County, Potential Uses of AVL and Framework for Evaluation

The study identified performance characteristics of the Santa Clara county bus system that could be improved using AVL. One section of this document includes an evaluation framework for assessing the potential benefits and costs of alternative strategies for improving transit performance. The data necessary for the baseline (no AVL) analysis includes:

- Total vehicles
- Transit operating expenses
    Vehicle operations
    Vehicle maintenance
    Non-vehicle maintenance
    General and administrative
    Purchased transportation
- Transit service characteristics
    Fleet size
    Vehicles operated in peak
    Vehicles operated in base
    Growth in vehicles operating in peak and base
    Vehicles operated – maximum service
    Vehicles available – maximum service
    Route miles
    Number of employees
    Number of employee hours
    Number of road calls
    Number of service interruptions
- Transit safety
    Number of incidents (collision, non-collision, station)
    Number of fatalities (patron, non-patron, total)
    Number of injuries (patron, non-patron, total)
- Transit service supplied
    Scheduled and annual vehicle revenue miles
    Actual annual vehicle miles
    Actual annual vehicle hours
    Actual annual vehicle revenue miles
    Actual annual vehicle revenue hours
- Transit service consumed
    Annual unlinked passenger trips
    Annual passenger miles
    Passenger delays.

The benefits from AVL accrue to transit users and the transit agency itself. User benefits include time savings in waiting for the bus and in-vehicle, better planning, improved safety, and reduced uncertainty. Transit agency benefits include reduced labor and vehicle costs, information accuracy for running times, reduced maintenance costs, increased safety, increased information, increased revenues, productivity improvements (reductions in vehicle running time fluctuations), service quality improvements, and vehicle running time improvements.

Equations are provided for various measures associated with schedule adherence and timed transfers, emergency and incident management, passenger information, transit operations information, and ridership. However, there is little to no information regarding the impacts from the AVL system.

Productivity Benefits and Cost Efficiencies from TMS Applications to Public Transit: The Evaluation of AVL

The research presented in this document uses Total Factor Productivity (TFP) techniques to identify opportunities for improving efficiency as a result of AVL systems. FTA Section 15 report data were used for 23 agencies covering the years 1988-1997. TFP regressions were estimated for three output measures: vehicle revenue miles, passenger miles, and passenger trips.

PATH researchers made several conclusions:

- A 10-percent increase in passenger-miles would increase TFP by 0.3 percent (expanding passenger miles will not lead to large increases in cost efficiency)
- A 1-percent increase in vehicle-miles of service will on average lead to a 0.6-percent increase in passenger trips
- A 1-percent increase in vehicle-miles increases costs by 0.25-percent (there are cost economies)
- A 1-percent increase in passenger-trips leads to a 0.25-percent increase in the number of buses.
- A 1-percent increase in vehicle-miles leads to a 0.96-percent increase in energy used
- A 1-percent increase in average trip length leads to a 0.22-percent reduction in energy used
- A 1-percent increase in vehicle hours leads to a 0.95-percent increase in maintenance hours.

Control Strategies for Transit Priority

The objectives of this study were to develop and evaluate strategies for transit priority with an emphasis on buses traveling along arterial facilities. The study assumed that there are no conflicting bus movements at the intersection approaches (no transit

vehicles on cross-streets), transit vehicles do not block travel lanes at the intersections approach for loading and unloading, signals are operating under optimal settings, and there are no incidents. Both passive (optimal signal timing favoring transit) and active signal priority strategies (bus preemption) were analyzed. The measures selected for use in the evaluation were impacts to transit (travel time and delay, schedule reliability and bus headway variation) and rest of traffic stream (travel time, delays, and stops).

The methodology for evaluating the impacts involved the use of the TRANSYT-7F model. A number of data were required for the analysis including: length of segment, number of intersections, number of lanes, signal spacing, type of intersection, signal phasing, bus frequencies, bus stop locations, dwell times, speeds, and volumes. Passive priority strategies resulted in a reduction in delay to buses of 14 percent and improved average bus speed by 3.4 percent (2 seconds/bus/intersection delay savings). Impacts to the rest of the traffic stream were marginal with total delay increasing by 1 percent and number of stops decreasing by 2 percent. Active priority strategies showed bus time savings of 0 to 6 seconds per intersection. The impacts to the rest of the traffic stream were insignificant.

3.8   Bus Rapid Transit (BRT)

SmartBRT: A Set of Planning, Analysis and Evaluation Tools for Bus Rapid Transit: Final Report Year 1 of 2

This document summarizes the first year results for the development of a toolbox, *SmartBRT*, for evaluating bus rapid transit (BRT) operations to aid in decision making. The toolbox includes visualization (three-dimensional graphics), interfaces to conventional traffic modeling tools, interfaces to planning tools, analytical tools for BRT concept developers, and short-term results. *SmartBRT* uses simulation (SHIFT/*SmartAHS* and Paramics) to assess various BRT operational concepts, such as physical facilities, bus configurations, scheduling, fare collection methods, and policies changes. It also can evaluate the effect of adding ITS technologies to BRT operations. ITS technologies that can be evaluated with BRT in *SmartBRT* include automatic vehicle location (AVL), automatic vehicle monitoring, signal priority, fare collection strategies, precision docking, and automated BRT operations. *SmartBRT* is being developed by PATH and the first-year development was funded by FTA and Caltrans New Technology and Research.

As part of the first year effort, *SmartBRT v1.0* was applied to a real case study, the Wilshire-Whittier (W-W) corridor in Los Angeles. In this case, BRT resulted in a 29-percent reduction in travel time from local transit time and a 25-percent increase in ridership. The Los Angeles County Metropolitan Transportation Authority (LACMTA) estimates that one-third of the improvement resulted from the bus signal priority component, while the other improvements made for BRT (exclusive bus lanes and limited stops) accounted for the other two-thirds of the time savings.

The case study version of the *SmartBRT* model was based on the following inputs: roadway geometry, running way (dedicated lane), number and location of stops, headway, demand (passengers per stop per hour), vehicle type (low-floor), dwell time, signal priority system, speed, maximum speed, acceleration, bus capacity, traffic volumes (corridor and cross street), green/red phase at signals, cost (capital and operation) for cost effectiveness evaluation. Although not fully developed, case-study *SmartBRT* demonstrates the potential for evaluating BRT. The second year of the study has not yet been approved, but potential tasks include enhancing the simulator, conducting site-specific analysis, and conducting additional off-line BRT analyses.

3.9   Other Research

Caltrans Non-Recurrent Traffic Congestion Study

Caltrans recently sponsored research to develop a comprehensive methodology for measuring, estimating, and modeling non-recurrent congestion throughout the year on the State Highway System as a whole based on available data. The methodology should also be able to distinguish between the types of non-recurrent congestion including incidents, weather, work zones, special events, etc.). The document contains a literature review, an assessment of user needs, a review of current Caltrans congestion management practices, recommended freeway surveillance methodology, recommended methodology for other facilities, an implementation plan, and conclusions and recommendations.

Currently, congestion data for Caltrans are collected and reported through the Highway Congestion Monitoring Program (HICOMP) annual report. Recurrent congestion is defined in the HICOMP as a "condition lasting for 15 minutes or longer where travel demand exceeds freeway design capacity and vehicular speeds decline to 35 mph or less during peak commute periods on a typical incident-free weekday." Non-recurrent delay is not measured directly but is assumed to be equal to recurrent delay. Recurrent delay is calculated by taking the difference between the actual travel time along a congested segment and the travel time had the speed been 35 mph.

The recommended methodology for measuring current incident related congestion for freeways is through the use of the Freeway Performance Measurement System (PeMS) surveillance data and incident data from the California Highway Patrol Computer-Aided Design (CHP/CAD) database. Total delay, recurrent and incident related delay can be estimated from these data. Recurrent delay would be the measured delay during a typical day (fair weather, no incidents, no work zones, no special events, no other events). Non-recurrent delay would be the total delay minus the estimated recurrent delay.

The recommended methodology for estimating non-recurring congestion for facilities without PeMS detection in place builds upon estimates of the various causes of delay: recurrent congestion, weather, incidents, work zones, special events, and other non-

recurrent events. It relies on data regarding geometric (route characteristics) and demand characteristics (volumes) for the facility and the probability of occurrence for non-recurrent events. The document contains detailed data requirements, methodology and equations for estimating the delay and are based on several assumptions. The minimum annualized data requirements for this method are:

- Geometric data – facility segment lengths, facility type, area type, terrain type, total lanes, and posted speed

- Demand data – AADT, peaking (K) factor, directional (D) factor, percent trucks, vehicle occupancy by segment of facility

- Collision history – total of collisions per year, or rate per vehicle mile for the study segment

- Maintenance/construction activity – number of days per quarter of lane closers and shoulder work by segment of facility

- Days of weather – number of days per year of snow or ice, fog, and rain

- Special events data – frequency by year

- Signal characteristics – number of signals on segment, average cycle length, average green per cycle ratio.

Inter-Technology Effects in Intelligent Transportation Systems

This PATH project estimated the benefits of varying combinations of ITS deployments (freeway service patrol, changeable message signs, and ramp metering) using the AIMSUN2 simulation model. The following assumptions were used in the analysis:

- Freeway free-flow speed = 88 km/hour
- Ramp free-flow speed = 60 km/hour
- State 1 traffic demand
    8,000 vehicles/hour at entrance section
    600 vehicles/hour on ramps
    0 to 45-minute period
- State 2 traffic demand
    10,000 vehicles/hour at entrance section
    600 vehicles/hour on ramps
    45 to 75-minute period
- State 3 traffic demand
    8,000 vehicles/hour at entrance section
    600 vehicles/hour on ramps
    75 to 120-minute period

- Actual demand on ramps set at 630 vehicles/hour
- Incidents activated after 30 minutes at fixed location with varying clearance rates
- Incident clearance of 20 minutes with no FSP, 10 minutes for both CMS and FSP
- Used adaptive ramp metering rates
- Network includes parallel roadways, ramp meters and CMS
- Downstream bottleneck has two upstream ramp meters with a CMS at the diverge point where a freeway with three lanes splits into two two-lane freeways; incident located after second ramp.
- CMS provides information to 100 percent of drivers, but the percentage of drivers changing travel behavior varies from 0 to 100 percent. If no CMS are deployed, a 50-percent split between two routes assumed, optimal with CMS and FSP.

The results show that consumers' surplus benefits are positive for congested networks. For both one- and two-lane incidents, the technologies typically generate more benefits separately than together (sub-additive). For the one-lane blockage, CMS and ramp metering are sub-additive but for two-lane blockages, they are produce more benefits than alone (super-additive). In incident conditions, FSP generate more benefits than either CMS or ramp metering. While many of the benefits may be sub-additive, there may be cost savings with deploying multiple technologies together.

4.0   CAL-B/C METHODOLOGY

The next few subsections describe the Cal-B/C methodology in terms of the specific algorithms, necessary data (e.g., lookup tables, factors, etc.), and their sources for each of the project types that were added to Cal-B/C as part of the recent update.

Each subsection is devoted to a specific type of project and provides the following discussion:

- Impacts Analyzed – identifies the specific impacts analyzed by the recommended approach.

- User Inputs – describes any new user-provided data required to complete the analysis that is not already included in the base version of Cal-B/C.

- Impact Calculation – describes the approach for estimating the incremental change on various impact categories due to the implementation of the project. This section also describes the process for assigning a dollar benefit value to the estimated impacts if it differs from the current Cal-B/C approach.

- Major Assumptions – identifies significant assumptions made or potential limitations of the Cal-B/C update methodology.

4.1   Ramp Metering

As outlined in the TMS Master Plan, several types of ramp metering exist in or are envisioned for California over the next several years including: simple adaptive, simple adaptive with optimized metering rates, and corridor adaptive schemes. Fixed-time metering systems may also exist in some parts of California, but they are not very prevalent and will not be built in the future.

The TMS Master Plan describes a logical progression among ramp metering types for highway corridors in California:

- Construct the infrastructure necessary for ramp metering and adopt simple adaptive strategies

- Adjust the metering rates so they are optimized for corridors

- Coordinate across ramp meters with centralized control and adopt corridor adaptive schemes.

Some California corridors are already testing corridor adaptive schemes while conditions along others may never justify moving beyond the simple adaptive metering. Regardless of the stage of any particular corridor, the majority of the capital funds will be spent constructing the infrastructure and adopting simple adaptive strategies. While some of the later stages may also require capital funding, Cal-B/C is more likely to be used to assess projects for the initial ramp metering construction and adoption of simple adaptive strategies.

As a result, Cal-B/C has been modified in the update to estimate the benefits of implementing simple ramp metering strategies on corridors that do not currently have ramp metering. This is consistent with the implementation framework laid out in the TMS Master Plan. It is also consistent with the typical ramp metering progression found in IDAS.

The analysis framework for ramp metering projects is designed to make the best use of available data on ramp metering impacts. In the best scenario, a given corridor has been modeled in detail so that speed and volume data are available for the highway network, ramps, and potential arterial alternatives. Cal-B/C is able to use the detailed output of a micro-simulation model or appropriate alternate approach and estimate the benefits of ramp metering projects.

If detailed data are not available, Cal-B/C is able to use the same basic inputs that are required for other highway projects. The model uses rules of thumb impacts developed from simulations conducted for the TMS Master Plan to estimate benefits and disbenefits on the highway, ramps, and arterials. Consistent with the TMS Master Plan, benefits and disbenefits on the ramps and arterials are estimated as percentages of the highway if detailed data are not available. The rules of thumb can be updated as additional simulations are conducted or other information becomes available.

Impacts Analyzed

The updated Cal-B/C estimates impacts for all four categories of user benefits found in the base version of the model:

- Travel time
- Number of accidents
- Vehicle operating costs
- Emissions.

User Inputs

The inputs required vary depending on whether detailed highway, ramp, and arterial data are available.

If detailed data are available, users need to provide the following:

- *Highway speeds and volumes* – Users need to input speeds in mph and volumes in vehicles for the peak period in Year 1 and Year 20 with and without the project. The information provided for the "peak period" should reflect the hours the metering is active and that were modeled. The data can be for a single highway or several in aggregate, depending on what was modeled in the micro-simulation providing the data. This information should be input into the detailed highway data in Box 2A of the "Model Inputs" sheet. Cal-B/C estimates speeds and volumes using the TMS Master Plan rules of thumb, but these data can be overridden by the user entering data in the green cells.

- *Aggregate ramp length* – This should reflect in miles the total length of on-ramps along the corridor being analyzed. The length should be consistent with the model providing the input data rather than the actual design length, so that travel time estimates on the ramps are accurate. Users can estimate the appropriate aggregate ramp length by dividing the total vehicle-miles traveled (VMT) on the ramps by the total ramp volume.

- *Ramp speeds and volumes* – Cal-B/C estimates benefits only for the period the metering is active, which is designated as the "peak period," regardless of the actual hours or length of the period. Users should input speeds in mph and volumes in vehicles in Year 1 and Year 20 with and without the project in aggregate for all ramps modeled. This should be entered as peak period data in Box 2C of the "Model Inputs" sheet and be consistent with the data entered for the highway.

- *Aggregate arterial length* – This should reflect in miles the total length of arterials along the corridor being analyzed. This can be for a single arterial or an entire network, depending on what was modeled in the micro-simulation providing the data. Users can estimate the appropriate aggregate arterial length by dividing the total vehicle-miles traveled (VMT) on the arterials in the simulation network by the total volume on the arterials.

- *Arterial speeds and volumes* – Cal-B/C estimates benefits only for the period the metering is active, which is designated as the "peak period," regardless of the actual hours or length of the period. Users should input speeds in mph and volumes in vehicles in Year 1 and Year 20 with and without the project in aggregate for the arterial(s) represented in the aggregate arterial length and for the same time period as entered for the highways and ramps. This should be entered as peak period data in Box 2C of the "Model Inputs" sheet.

If detailed data are not available, users should provide the same basic inputs that they would for any highway projects with a few changes:

- *Number of hours of ramp metering operation* – Users should enter as the length of the peak period, the number of hours that the ramp metering is active. If this is a long period of time, the default for the average percent of average daily traffic (ADT) that occurs during a peak hour found in the parameters section of the model must be adjusted so that the total percent of ADT calculated for ramp metering operation is correct.

- *Number of lanes* – This should reflect the portion of the freeway that is impacted by ramp metering.

- *Average daily traffic* – Users should enter in the model the average daily traffic as they would for other highway projects. If users chose to enter highway volumes for the ramp operating period only, then the length of the peak period and the percent ADT during a peak hour should be adjusted so that the peak period equals 100 percent of ADT.

- *Highway capacity per lane* – Cal-B/C includes a default for the per lane capacity of a highway (2000 vehicles per hour per lane, vphpl). Users should not change this capacity, even if they think ramp metering will effect the capacity. Cal-B/C estimates speeds using a BPR curve calibrated to 2000 vphpl and adjusts these speeds for ramp metering impacts using rules of thumb consistent with the TMS Master Plan. Adjustments to the highway capacity will change the speeds estimated.

- *Number of metered on-ramps* – Although this information is not needed for Cal-B/C, it should be provided by Caltrans districts so the capital, operating, and maintenance costs provided can be compared to those in the TMS Baseline Inventory.

Impact Calculation

Cal-B/C takes two different approaches for estimating the benefits or ramp metering depending on the data provide by the user:

- Approach 1 describes the methodology for calculating impacts if detailed ramp and arterial data are not available. This approach is the default. Benefits are estimated using rules of the thumb consistent with the TMS Master Plan.

- Approach 2 describes the methodology for calculating impacts if detailed ramp and arterial data are available. In this case, the benefit calculation is simpler because all the necessary volume and speed data are provided by the user.

Approach 1: Detailed Data Not Available

- Cal-B/C generally estimates for highway projects detailed volume and speed data from simple inputs and presents the results for the user to verify in the "Model Inputs" section of the model. Speeds are calculated using a standard BPR curve.

- If detailed data are not available for ramp metering project, the Cal-B/C update continues to calculate highway speeds and volumes as they were previously. However, they are adjusted to account for the ramp metering impacts using rule of thumb percentages consistent with the TMS Master Plan. The speed and volume adjustments are found in a lookup table in the parameters section of the model and can be updated as more recent simulations are conducted. Users can review and adjust these estimates (although this is not recommend if detailed data are not available) in the "Model Inputs" section.

- **Travel time** benefits for the highway section are calculated using the resulting speed and volume data. The detailed calculations also include estimates of benefits (or disbenefits) occurring on ramps and arterials. These are estimated as percentages of the benefits occurring on the highway since detailed ramp and arterial data are not available. The default values used to estimate these benefits are included in the parameters and are consistent with the TMS Master Plan. The final benefit calculation is adjusted using an adjustment factor.

- Benefits for **vehicle operating costs, accident reductions, and emissions** are calculated in a similar manner. The model uses the speed and volume data found on the "Model Inputs" page to estimate highway benefits using the standard Cal-B/C methodology. Ramp and arterial benefits and disbenefits are added as percentages of the highway benefits and the final benefit calculation is adjusted.

- The impact of ramp metering on the number of accidents is calculated consistent with the default impact found in IDAS, which is a 30-percent decrease in the overall highway accident rate. The TMS Master Plan assumed that ramp metering did not impact accident rates to be conservative in the benefit estimation.

Approach 2: Detailed Data Available

- If detailed data are available for a ramp metering project, the user can override the default highway speeds and volumes estimated by the model. Box 2A of the "Model Inputs" page provides the model estimates using the TMS default values. The user can input detailed highway data in the green cells next to the model calculated values. If the user inputs data in these cells, the model uses these speeds and volumes automatically for the calculation of the highway benefits and does not make the final benefit adjustment.

- The user enters detailed data for the ramps and arterials in Box 1C of the "Model Inputs" sheet. A critical entry is the yes or no for the "is detailed data available" question. If yes is entered, the model estimates benefits for the ramps and arterials using data provided by the user. If no is entered, the model estimates benefits for the ramps and arterials as percentages of the highway benefits using the default values from the TMS Master Plan. The model automatically selects yes if the user enters any data in the boxes for ramps and arterials.

- When detailed data are available, the model calculates the user benefits on the ramps and arterials using the standard Cal-B/C methodology but

with the ramp and arterial speeds and volumes. Cal-B/C includes a statewide accident rate for arterials in the parameters section of the model. This rate is used to calculate safety benefits on the arterials. Although the accident rate can be changed by the user, the model uses the same accident rate for the before and after case so benefits are a function of the change in vehicle-miles traveled only.

Major Assumptions

- Cal-B/C assumes that the project has been scoped correctly to include the field elements and associated costs to implement ramp metering strategies fully.

- The TMS Master Plan takes a corridor approach to ramp metering deployment. This is also consistent with the Department's direction towards corridor planning. However, unlike some of the other improvements analyzed in Cal-B/C ramp metering could be deployed discontinuously (and have few benefits). For example, a length of highway corridor may have five on-ramps, but only three of these are equipped with ramp metering capabilities. Cal-B/C assumes that the user has entered data for homogenous (metered or not) segments.

- Arterial facilities may experience different accident rates than the highway. Cal-B/C assumes that the accident rate on the arterials equal the statewide average and that ramp metering does not affect the arterial accident rate.

- Vehicle operating cost and emissions rates are assumed to be the same across all three facilities: highway, ramps, and arterials. The default TMS adjustments include very conservative assumptions about emissions at ramps to make sure benefits are not overstated.

4.2   Signal Coordination with Ramp Metering

The analysis framework for signal coordination with ramp metering is nearly identical to the methodology for ramp metering. As with ramp metering, users may enter detailed data for the highway, ramps, and arterials and the model estimates benefits from these inputs. If detailed data are not available, the model estimates benefits using the rules of thumb developed in the TMS Master Plan, which has separate adjustments for ramp metering and signal coordination with ramp metering.

Impacts Analyzed

The updated Cal-B/C estimates impacts for all four categories of user benefits found in the base version of the model:

- Travel time
- Number of accidents
- Vehicle operating costs
- Emissions.

User Inputs

The inputs are the same as for ramp metering.

Impact Calculation

The impact calculation is also the same as for ramp metering. However, the **safety benefits** do not include the 30 percent reduction in accident rates, since these are assumed to have already occurred with the initial implementation of ramp metering. The default speed and volume adjustments for signal coordination with ramp metering are consistent with the TMS Master Plan and different from those for ramp metering alone.

Major Assumptions

The model makes the same assumptions for signal coordination with ramp metering as for ramp metering alone with the following additions:

- The signal coordination component of the deployment is assumed to be operated only in coordination with the ramp metering components. Therefore, the signal coordination is assumed to be operational during the identical time periods that the ramp meters are operational.

- Cal-B/C assumes that ramp metering has been implemented prior to the coordination with signal management.

4.3   Incident Management

The analysis framework for incident management projects is nearly identical to the methodology for ramp metering. As with ramp metering, users may enter detailed data for the highway, ramps, and arterials and the model estimates benefits from these inputs. If detailed data are not available, the model estimates benefits using the rules of thumb developed in the TMS Master Plan, which has different adjustments for incident management projects.

Impacts Analyzed

Cal-B/C analyzes changes in:

- Incident-related delay
- Number and severity of accidents
- Vehicle operating costs
- Emissions.

<u>User Inputs</u>

The inputs are the same as for ramp metering.

<u>Impact Calculation</u>

The impacts of incident management projects are calculated in a manner nearly identical to that for ramp metering with the following adjustments:

- Cal-B/C includes a default set of speed and volume adjustments for incident management projects that are consistent with the TMS Master Plan and different from those for ramp metering.

- The model estimates the change in **accident** severity using a method consistent with IDAS. The approach does not estimate an overall decrease in the number of accidents, but estimates a reduction in severity instead. Consistent with the methodology found in IDAS, the number of fatality accidents is reduced by 21 percent and the reduction is added to the total number of injury accidents in the with incident management case. The TMS Master Plan did not include estimation of accident benefits to be conservative in the benefit estimation.

- For **travel time** benefits, incident-related delay is monetized at three times the value of time to reflect the premium associated with uncertainty. This value is consistent with the multiple used in IDAS.

<u>Major Assumptions</u>

- Cal-B/C assumes that the project has been scoped correctly to include the field elements and associated costs to implement incident management strategies fully.

- Arterial facilities may experience different accident rates than the highway. Cal-B/C assumes that the accident rate on the arterials equal the statewide average and that incident management does not affect the arterial accident rate.

- Vehicle operating cost and emissions rates are assumed to be the same across all three facilities: highway, ramps, and arterials.

4.4 Real-Time Traveler Information

A number of TMS field elements can be deployed and used in association with providing travelers with real-time traveler information, such as Highway Advisory Radio (HAR), Changeable Message Signs (CMS), and Interactive Traveler Information Systems including Telephone-Based and Web/Internet-Based Traveler Information Systems and Kiosks. In the updated Cal-B/C model, real-time traveler information is evaluated as an overall corridor strategy rather than the sum of benefits associated with individual separate field elements. The approach is consistent with that taken in the TMS Master Plan.

The analysis framework for traveler information projects is nearly identical to the methodology for ramp metering. As with ramp metering, users may enter detailed data for the highway, ramps, and arterials and the model estimates benefits from these inputs. If detailed data are not available, the model estimates benefits using the rules of thumb developed in the TMS Master Plan, which has different adjustments for traveler information projects.

Impacts Analyzed

The updated Cal-B/C estimates impacts for all four categories of user benefits found in the base version of the model:

- Travel time
- Number of accidents
- Vehicle operating costs
- Emissions.

User Inputs

The inputs are the same as for ramp metering.

Impact Calculation

The impacts of incident management projects are calculated in a manner nearly identical to that for ramp metering except that the default set of speed and volume adjustments for traveler information projects are different from those for ramp metering and consistent with the TMS Master Plan.

Major Assumptions

- Cal-B/C assumes that the project has been scoped correctly to include the field elements and associated costs to implement incident management strategies fully.

- Arterial facilities may experience different accident rates than the highway. Cal-B/C assumes that the accident rate on the arterials equal the statewide average and that incident management does not affect the arterial accident rate.

- Vehicle operating cost and emissions rates are assumed to be the same across all three facilities: highway, ramps, and arterials.

- The resulting impacts on accidents, emissions, and vehicle operating costs should be carefully compared with observed results from real-world before and after studies of traveler information systems. These impacts of these systems have often been shown to be largely trivial for these deployments.

4.5 Arterial Signal Management

In the Cal-B/C model, Arterial Signal Management projects can include any of the following types of signal improvements: Isolated Fixed-Time Traffic Signals, Isolated Traffic Actuated Signals, Pre-set Corridor Signal Coordination, Actuated Corridor Signal Coordination, and Central Control Signal Coordination. However, Cal-B/C does not include any rules of thumb to estimate the benefits of these projects. They require complex modeling that is better handled in a signal optimization model. Users must first run signal optimization models and enter the results into Cal-B/C to conduct the economic assessment.

Impacts Analyzed

Cal-B/C estimates the benefits of changes in:

- Travel time
- Number of accidents
- Vehicle operating costs
- Emissions.

User Inputs

Cal-B/C allows users to enter detailed speed and volume data for arterials on the "Model Inputs" page. When the Arterial Signal Management project type is selected, Cal-B/C automatically prompts users to enter the following information:

- *Aggregate segment length* – Users must enter the aggregate segment length for the project and included in the signal optimization model. This may include cross-streets, if the optimization model includes this traffic. The segment length can be calculated as vehicle-miles traveled divided by the total volume.

- *Speed and volume data* – Users must enter speed and volume data for Year 1 and Year 20 with and without the project. Cal-B/C accepts arterial data for the peak period only. If only all-day data are available, these can be inputted in place of the peak period data and the peak period percent in the Parameters section can be modified to be 100 percent. If both peak and non-peak data are available and they are substantially different, the peak and non-peak analyses must be conducted separately and added.

Users may also modify the accident rates to be applied to the with scenario if they have data to support this change.

Impact Calculation

- The impact to **travel time** is calculated by calculating the difference in delay between the with and without scenarios, using the following formula:

  TT = (Dwithout – Dwith) * Average Vehicle Occupancy * 365 days per year

  Where:
  TT = annual travel time savings
  Dwithout = daily hours of vehicle delay without project
  Dwith = daily hours of vehicle delay with project

  If vehicle-hours of delay data are available, they can be entered directly into the detailed travel time calculation tables for arterials.

- Impacts to **emissions** and **vehicle operating costs** are calculated using the existing Cal-B/C methodology, based on any changes in speeds input by the user. If the speeds are unadjusted by the user, no impacts to these measures are calculated.

- **Accident impacts** are calculated using the existing Cal-B/C methodology, based on any changes in speeds or accident rates input by the user. If the speeds or accident rates are unadjusted by the user, no impacts to these measures are calculated

The benefits in dollars per year are calculated by multiplying the various impacts by the appropriate unit value, as per the existing Cal-B/C methodology.

Major Assumptions

- Analysis does not account for any traffic diversion to/from parallel roadways, or impacts to cross streets as a result of the project implementation, unless those impacts are included in the signal optimization analysis.

4.6 Automatic Transit Vehicle Location and Scheduling

The Cal-B/C update evaluates transit TMS projects in terms of aggregate transit benefits rather than the origin-destination based transit trips and travel times found in IDAS, since more detailed data are unlikely to be available. This approach is consistent with the prior Cal-B/C model.

Impacts Analyzed

- Unlike the prior Cal-B/C model, the updated model considers both in-vehicle and out-of-vehicle travel time impacts for transit TMS projects. This distinction is an improvement over the previous method since it allows in-vehicle and out-of-vehicle travel time to be monetized using different rates that account for the increased disutility of waiting time (as documented in the original Cal-B/C research on the value of time).

- The model also considers agency cost reductions, which can be major benefits for automatic transit vehicle location and scheduling systems. However, these reductions are agency cost reductions, rather than user benefits, and are included in the cost side of the analysis.

- Emissions and accident reduction benefits are calculated using the existing Cal-B/C methodology and any changes in transit vehicle miles of travel or accident rates inputted by the user.

User Inputs

- The user inputs in Cal-B/C have been changed so that the average transit travel time inputs have been split into *in-vehicle and out-of-vehicle transit travel time*. Users must input travel times with and without the project. These inputs can often be obtained from regional travel models.

- The user may also choose to evaluate the impacts of automatic transit vehicle location and scheduling systems on transit costs. Efficiency gains due to the deployment may result in a decrease in agency capital or operating/maintenance costs. If the user chooses to include these cost reductions in the analysis, the user must enter the *annual capital expenditure* and the *annual operations and maintenance expenditure* for the transit agency.

- The user may also choose to adjust other transit vehicle parameters including *annual vehicle miles* or the *percent reduction in transit accidents*. Impacts such as transit vehicle emissions and accidents are not analyzed by the framework unless the user modifies these figures.

Impact Calculation

- **Travel time** impacts for automatic transit vehicle location and scheduling systems are calculated by comparing the travel time with and without the project. Cal-B/C includes a default reduction in in-vehicle and out-of-vehicle travel time with the project of 15 percent. This default is included in the parameters section of the model and can be changed by the user. The user may also change the with project travel times estimated by the model on the "Project Information" page.

- In-vehicle and out-of-vehicle travel times are multiplied by the *Annual Transit Person Trips* to calculate the travel time for the new facility scenario. The user should make sure to only enter information on transit trips or routes that are affected by the project. If these routes are substantially different, then they must be analyzed separately.

- Impacts on travel time for other modes due to a shift in trips to transit are calculated using the existing Cal-B/C analysis, assuming the user has entered a value in the *Percent New Trips for Parallel Highway*.

- The monetization of travel time benefits in the updated Cal-B/C differs slightly from the existing Cal-B/C approach which applies a standard value of time to all travel time savings. The new model calculate in-vehicle and out-of-vehicle time separately. Impacts to these performance measures are valued differently:

  - In-vehicle travel time is monetized using the standard travel time value applied in Cal-B/C.
  - Out-of-vehicle travel time is monetized using a value twice times the standard value of travel time. This increased valuation reflects the uncertainty, exposure to weather conditions, and concerns for security that may accompany out-of-vehicle wait times.

- Changes in agency costs are calculated only if the user provides the required inputs. If these data are provided, the model applies a default 2-percent reduction to the *Annual Capital Expenditure* figure and applies a default 8-percent reduction to the *Annual Operations and Maintenance Expenditure* figure. The resulting reductions are summed and included as a negative cost in the Project Cost calculations. The reductions are

consistent with the factors included in IDAS and may be modified in the parameters section. *Annual Capital Cost Savings* represent a reduction in the amount of funding required for vehicle purchases and other transit infrastructure. *Annual Operations and Maintenance Cost Savings* represent a reduction in the amount of funding required for fuel, labor, maintenance, and other continuing costs.

- The valuation of benefits for emissions and accidents uses the existing Cal-B/C methodology. Emissions and accident benefits are calculated if the user indicates any changes in transit vehicle miles of travel or accident rates.

Major Assumptions

- It is assumed that the user inputs only information (person trips, vehicle-miles, travel times, agency costs, etc.) relevant to services or routes impacted by the transit TMS improvement. If only a portion of services or routes are impacted, then the data inputted should reflect only this portion.

- Accident and emissions benefits are assumed to be a product of a reduction in vehicle-miles traveled. Reductions in rates are not considered.

4.7   Transit Vehicle Signal Priority

As with automatic transit vehicle location and scheduling project, the Cal-B/C update examines transit vehicle signal priority projects in terms of aggregate transit benefits rather than the origin-destination based transit trips and travel times found in IDAS, since more detailed data are unlikely to be available. The methodology for estimating the benefits of signal priority projects is the same as for other transit TMS projects, but some of the default values are different.

Impacts Analyzed

- The updated Cal-B/C model considers both in-vehicle and out-of-vehicle travel time impacts for transit TMS projects.

- Emissions and accident reduction benefits are calculated using the existing Cal-B/C methodology applied to any user input changes in transit vehicle miles of travel or accident rates.

User Inputs

The user inputs for transit vehicle signal priority are the same as those for automatic transit vehicle location and scheduling systems, except that transit agency expenditure information is not needed. Signal priority projects do not result in agency cost savings.

Impact Calculation

- **Travel time** impacts for transit vehicle signal priority are calculated as they are for automatic transit vehicle location and scheduling systems. However, the travel time impacts for these projects are limited to changes in in-vehicle time only. The PATH research on bus rapid transit included transit vehicle signal priority as a component of BRT. The PATH research found that bus rapid transit systems produce an aggregate savings in in-vehicle travel times of 29 percent and that one-third of this is due to the signal priority component. Cal-B/C includes a default in-vehicle travel time improvement of 10 percent for transit vehicle signal priority systems. This is also consistent with values found in IDAS. The default value can be changed in the parameters section of the model.

- Emissions and accident reduction benefits are calculated using the existing Cal-B/C methodology applied to any changes in transit vehicle miles of travel or accident rates inputted by the user.

Major Assumptions

- Cal-B/C assumes that travel time benefits for non-transit arterial traffic and cross traffic cancel and ignore modeling any impacts to these travelers.

4.8   Bus Rapid Transit

The Cal-B/C update examines transit TMS projects in terms of aggregate transit benefits rather than the origin-destination based transit trips and travel times found in IDAS, since more detailed data are unlikely to be available. This approach is consistent with the prior Cal-B/C model.

Impacts Analyzed

- The updated Cal-B/C model considers both in-vehicle and out-of-vehicle travel time impacts for transit TMS projects.

- Emissions and accident reduction benefits are calculated using the existing Cal-B/C methodology applied to any user input changes in transit vehicle miles of travel or accident rates.

<u>User Inputs</u>

The user inputs for bus rapid transit are identical to those for transit vehicle signal priority projects.

<u>Impact Calculation</u>

- The **travel time** impacts for bus rapid transit projects are calculated in the same manner as they are for signal priority projects. Cal-B/C includes a default reduction in in-vehicle travel time of 29 percent. This default is based on the PATH research into bus rapid transit systems and can be changed by the user in the parameters section of the model. Out-of-vehicle travel times are not impacted.

- Emissions and accident reduction benefits are calculated using the existing Cal-B/C methodology applied to any user input changes in transit vehicle miles of travel or accident rates.

<u>Major Assumptions</u>

- Cal-B/C assumes that travel time benefits for non-transit arterial traffic and cross traffic cancel and ignore modeling any impacts to these travelers.

V. OPERATIONAL IMPROVEMENTS

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During an initial meeting for the most recent update to Cal-B/C, the project Advisory Committee identified operational improvements to include:

- *Auxiliary Lanes* – These lanes connect freeway on-ramps to nearby off-ramps. They facilitate lane changing activity by providing vehicles more time and distance to merge on and diverge off freeways.

- *Freeway Connectors* – These are extended ramps that connect two or more intersecting freeways. They allow travelers to change freeways without exiting the freeway system.

- *High Occupancy Vehicle (HOV) Connectors* – Like freeway connectors, HOV connectors are extended ramps, but they directly connect HOV lanes on two or more intersecting freeways. The connectors eliminate the necessity for HOV travelers to change lanes and access standard freeway connectors.

- *HOV Drop Ramps* – Entry and/or exit ramps providing HOV-only access to and from HOV lanes. They allow HOV travelers to access HOV lanes directly from surface streets and eliminate the need to merge across multiple lanes.

- *Off-Ramp Widening* – The addition of lanes to existing freeway off-ramps to increase exit capacity. The extra capacity helps to avoid backups onto the mainline freeway lanes.

- *On-Ramp Widening* – The addition of lanes to existing freeway on-ramps to increase storage capacity. The extra capacity provides space for vehicles waiting to enter freeways, particularly in connection with ramp metering, and helps to eliminate gridlock on surface streets.

This section discusses issues relevant to evaluating these operational improvements and the methodologies used in the update Cal-B/C. After this introduction, the section is organized as follows:

- *Factors Affecting Operational Improvements* – provides a more detailed description of each operational improvement and identifies a few critical factors to be considered in evaluating their cost effectiveness.

- *Existing Caltrans Methodology* – describes Caltrans resources on operational improvements, such as databases, models, design manuals and methodologies for evaluating effectiveness.

- *Other Methodologies* – reviews the way other computerized benefit-cost models handle operational improvements.

- *Recent Research and Findings* – discusses findings from recent theoretical research with particular emphasis on the benefits and impacts of operational improvements.

- *Cal-B/C Methodology* – explains how each of the TMS improvements are included in the updated Cal-B/C model.

1.0   FACTORS AFFECTING OPERATIONAL IMPROVEMENTS

The project Advisory Committee included representatives from the Divisions of Transportation Planning, Traffic Operations, and Research and Innovation. The Advisory Committee decided that the update should address the most important and frequently funded projects. Special studies could be performed for projects that are occasionally funded or unique.

The group noted that a few types of the more common operational improvement (e.g., passing lanes, truck climbing lanes, and High Occupancy Vehicle lanes) were already included in the base version of Cal-B/C. The methodology that Cal-B/C uses to model these projects is documented in Volume 1 of the Technical Supplement to the User's Guide. However, a number of other operational improvements are not currently included in the model:

- Auxiliary Lanes
- Freeway Connectors
- HOV Connectors
- HOV Drop Ramps
- Off-Ramp Widening
- On-Ramp Widening.

The Advisory Group also considered including the evaluation of High Occupancy Toll (HOT) lanes in the Cal-B/C update. HOT lanes allow drivers of vehicles not otherwise eligible to pay a toll and use HOV lanes. The group decided that modifications to the model were not necessary to handle these projects. Cal-B/C can already accommodate these projects by increasing the number of "HOV" vehicles (and decreasing the number of "Non-HOV" vehicles accordingly) and lowering the average vehicle occupancy for HOVs in the after case to account for the new vehicles using the HOT lane.

The next few sections provide definitions for the improvement types included in the model update and identify factors to consider in evaluating them.
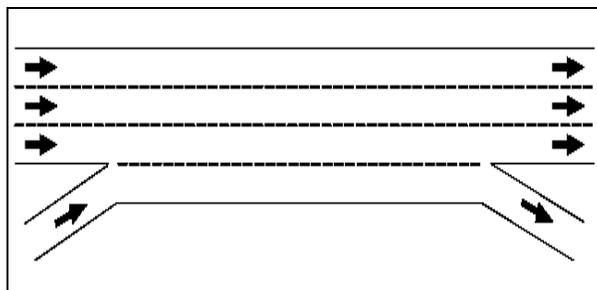
1.1   Auxiliary Lanes

Definition

The California Highway Design Manual defines auxiliary lanes as "the portion of the roadway for weaving, truck climbing, speed change, or for other purposes supplementary to through traffic movement." For the purposes of this report, auxiliary lanes are connect freeway on-ramps to nearby off-ramps to facilitate lane changing activity by providing vehicles more time and distance to merge on and diverge off freeways. Under this subset of the Design Manual definitions, auxiliary lanes are one of many tools to reduce traffic disruptions caused by weaving.

The 2000 Highway Capacity Manual (HCM) defines weaving as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway, without the aid of traffic control devices (except for guide signs)." (HCM 2000, p. 5-18) The HCM further classifies weaving sections by type, which is a function of geometric configuration and lane changing maneuvers. For the purpose of this paper, focus is given to a simple ramp-weave freeway section that is formed by consecutive on-ramps and off-ramps joined by an auxiliary lane. An example is shown in Exhibit V-1.

Exhibit V-1
Example of a Simple Ramp-Weave Area

Source: 2000 Highway Capacity Manual

Auxiliary lanes facilitate weaving areas by providing motorists a longer distance to merge on or diverge off freeways. This improves safety by allowing vehicles more time to accelerate or decelerate to the appropriate speed, and as a result, create less disruption to the flow of traffic in the through lanes. These lanes primarily benefit highway users in outside lanes. Theoretically, the lanes reduce accident rates and increase speeds and capacity in the outside lanes. However, if drivers systematically continue to the end of the auxiliary lane before merging, the benefits are reduced substantially. In this case, benefits accrue primarily to auxiliary lane drivers and are the result of allowing them to bypass freeway congestion for a limited distance.

Auxiliary lanes also accommodate higher traffic volume without the need to build additional freeway lanes. This improves traffic operations by both reducing total delay and increasing the number of vehicles that could move through the freeway weaving area, particularly during peak hours. Auxiliary may have the unintended effect of allowing some vehicles to bypass congestion on parallel surface streets by using the freeway for a limited number of exits (typically one, but may be more if the auxiliary lane spans multiple interchanges).

Factors to Consider

To accommodate the analysis of auxiliary lanes in Cal-B/C, several factors need to be considered:

- Lane length – The length of an auxiliary lane determines the distance available for entering or exiting vehicles to complete weaving maneuvers. Longer lanes may reduce disruptions on freeway through lanes. However, extremely long lanes may encourage drivers to continue to the end of the lanes, thereby reducing substantially the benefits due to facilitated merges.

- Number of lanes in the weaving area – Weaving substantially reduces the capacity of highway lanes, but not every lane on a freeway may be impacted by weaving. For instance, weaving near on-ramps and off-ramps may affect traffic in the right-most lanes, leaving the remaining lanes traveling at near free-flow conditions. Auxiliary lanes increase the capacity of these lanes by facilitating merging. Cal-B/C must be able to explicitly consider the traffic directly impacted by merging and diverging.

- Number and proximity of interchanges – The spacing between interchanges determines the distance available for auxiliary lanes to facilitate merging and diverging. Each interchange introduces a new perturbation in the traffic stream.

- Lane balance – Weaving sections are the result of two or more traffic streams joining and separating. Lane balance refers to the physical number of lanes before and after the weaving section and their ability to handle the relative volume of the weaving traffic streams. Balanced weaving sections can generally carry more traffic than imbalanced sections.

- Vehicle speed – Speed is a function of the volume and capacity of the highway section. Weaving reduces the capacity and, as a result, the speed. Vehicle speeds vary across the roadway by whether the lanes are

influenced by weaving or not. Weaving operations require the standard speed calculation in Cal-B/C to be modified.

- Induced demand – In some cases, the addition of the auxiliary lane may attract from parallel arterials motorists wanting to take advantage of higher speeds by entering, traveling along the auxiliary lane, and immediately exiting the freeway. From the perspective of the freeway system, these are induced travelers. If the parallel arterials are included in the analysis, these are route shifts, but other motorists may use the freed capacity on the parallel arterial. Before and after conditions on parallel arterials need to be considered if the induced effect is large.

1.2   Freeway Connectors

Definition

Connectors are roadways that provide ingress and egress to freeways and to the user act like extensions of freeways. Although connectors usually consist of only one or two lanes, have tighter turning radii than freeways, and lower speeds than freeways, engineers try to apply uniform geometric design standards to ease the transitions. Connectors may join a freeway with surface roads, other freeways, or other facilities.

Connectors that join two or more freeways allow travelers to change freeways without exiting the freeway system. These connectors are typically called freeway-to-freeway connectors, which the California Highway Design Manual defines as "a single or multilane connection between freeways." For the purposes of this paper and the Cal-B/C update, these connectors are called "freeway connectors." A group of freeway connectors form a freeway-to-freeway interchange, which the Design Manual explains "link(s) freeway segments together so as to provide the optimum highway system."

As for most roadway types, user benefits for freeway connectors can be calculated from speeds and volumes for traffic using the connector. Like auxiliary lanes, connectors create merging and weaving conditions. As a result, impacts must be modeled for users of both the mainline freeway and the freeway connectors. Most freeway connector projects in California are improvements for existing connectors. Improperly designed connectors can cause backups that spill onto the mainline. In addition, the impacts of weaving may persist for an affected area beyond individual connectors. If a connector does not replace an existing connector, then the model would need to take into account the alternative routing users must take in the absence of a connector and use data for this routing. It is also possible that connectors may influence travel demand.

The analysis of connectors is complicated by their geometry. Since freeway connectors join two freeways, conditions on both mainlines must be modeled with their own weaving areas. A full freeway interchange can include eight connectors that provide ingress and egress to all four travel directions. Although basic interchange

configurations can vary, Exhibit V-2 illustrates a direct interchange with two of the eight connectors highlighted. In the standard design, connector generally connect the rightmost lane of one freeway with the rightmost lane of the second freeway.

Modeling the entire interchange would require ten areas (the two mainline freeways and the eight connectors) to be considered. It may be possible to use a weighted average impact on speed and volume for all the connectors and the weave areas.

As with other highway treatments that handle merging conditions, improvements to freeway connectors may reduce accident rates.

Exhibit V-2
Examples of Freeway-to-Freeway Connectors
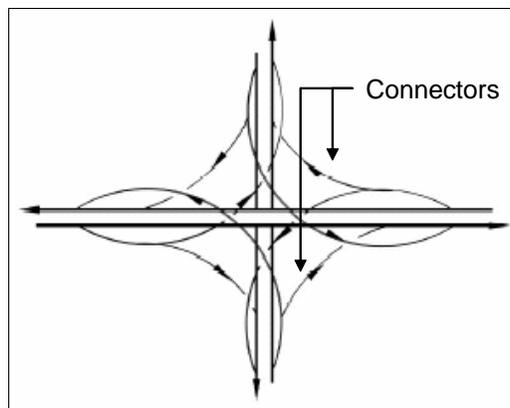
Source: California Highway Design Manual

Factors to Consider

To accommodate the analysis of freeway connectors in Cal-B/C, several factors need to be considered:

- Capacity on connector – The capacity of an individual connector can be influenced by a number of factors, such as the number of lanes, curvature, and sight distance. Connectors often consist of a single lane, but two-lane connectors are not uncommon at California interchanges with high demands.

- Speed on connector – The capacity of the connector directly impacts the speed, which is typically lower than on the mainline freeway.

- Demand for using connector – Each of the eight connectors in a freeway interchange may have a different volume. If demands are fairly symmetrical, only four sets of bi-directional movements would need to be analyzed. Analyzing a single connector would simply the analysis further.

- Weaving movements – Speeds and volumes on the mainline freeways are impacted by weaving movements. The analysis of weaving impacts is similar to that for auxiliary lanes, including the need to examine weaving volumes and lane balance. Unlike for auxiliary lanes, the impact on two freeways must be considered.

- Alternative routings – If the connector being analyzed is a new one, the analysis must consider the routes travelers took prior to the connector being built. These may involve the same freeways, different freeways, surface roads, or combinations.

- Accident rates – Interchange geometrics and weaving flows can impact accident rates for the facility. A new connector that is better adapted to present and future traffic patterns may reduce accident rates.
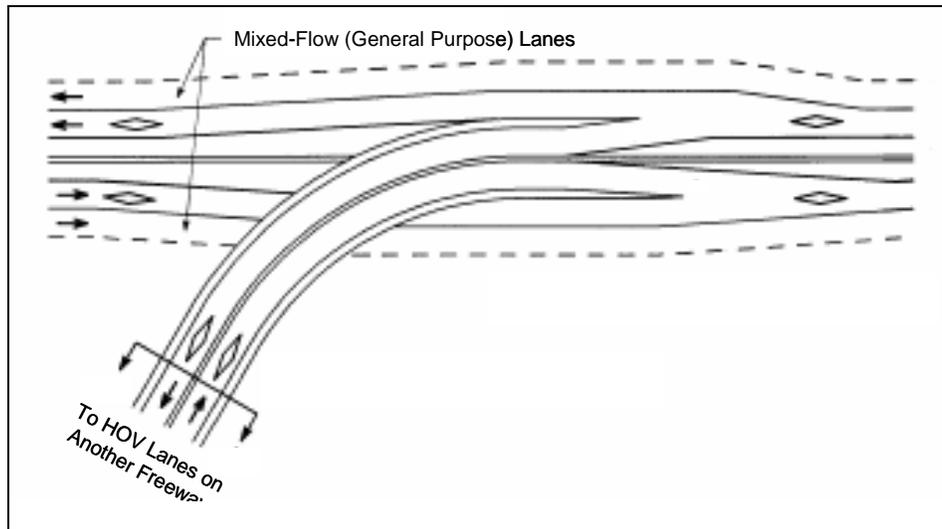
1.3 HOV Connectors

Definition

HOV connectors are another type of connector found on freeways. An HOV connector provides a direct link between HOV lanes on one freeway to HOV lanes on another freeway. Like freeway connectors, HOV connectors operate as extended ramps between two freeways. Unlike freeway connectors, HOV connectors are available only to HOVs.

Freeway connectors are usually located near the rightmost lanes. As illustrated in Exhibit V-3, HOV connectors eliminate the necessity for HOV travelers to weave across mixed-flow lanes to access these connectors. HOV connectors directly access the HOV lanes on the left side of the freeway.

HOV direct connectors provide benefits for both HOVs and single occupant vehicles by reducing accidents rates and increasing speeds and volumes. HOV connectors can involve significant capital costs, but they may be warranted in areas with extensive HOV networks (such as in Southern California) and significant travel demand.

Exhibit V-3
Example of an HOV Connector

Factors to Consider

To accommodate the analysis of HOV connectors in Cal-B/C, all of the factors described for freeway connectors need to be considered, plus:

- HOV requirement – The number of passengers (vehicle occupancy) required for vehicles to qualify as HOVs vary across California. Vehicles with two or more passengers are allowed to travel on most HOV facilities. However, some facilities require three or more passengers.

- HOV demand – The demand for HOV and non-HOV vehicles must be considered separately since vehicles not meeting the occupancy requirements are excluded from HOV facilities.

- HOV lane capacity and speed - As detailed in the technical documentation for the Cal-B/C model, volumes on HOV lanes are held under a threshold to minimize the chances of congestion on the lanes and guarantee the travel time benefit for HOV users. As a result, HOV lanes typically have lower capacities but higher speeds than mixed-flow lanes.

- Accident rates – Accidents are more likely to be a factor due to the speed differentials between HOV lanes and mixed-flow lanes. HOV connectors reduce the number of HOV/non-HOV conflicts that occur.
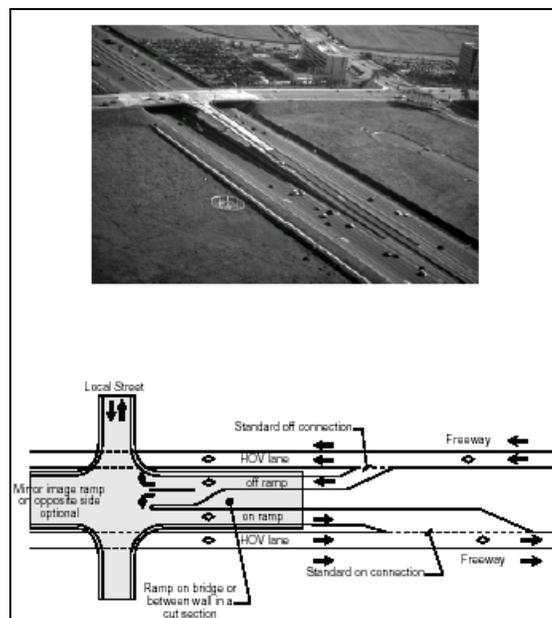
1.4   HOV Drop Ramps

Definition

Several types of direct access ramps provide exclusive ingress and egress for HOVs (vehicles meeting the HOV requirement such as buses, vanpools, and carpools). Potential design treatments include drop ramps, T-ramps, Y-ramps, and flyover ramps. While some of the other treatments may provide access to park-and-ride lots and transit stations located in the median of the freeway, drop ramps generally provide access from adjacent roadways to HOV lanes.

As shown in Exhibit V-4, drop ramps allow HOV travelers to access HOV lanes directly from surface streets and eliminate the need to merge across multiple lanes. HOV drop ramps are the HOV equivalent of on-ramps and off-ramps as HOV connectors are the HOV equivalent of freeway connectors. While drop ramps may involve significant capital costs, the travel time savings provide to HOVs and safety benefits afforded to all travelers may justify the additional costs associated with these treatments. Drop ramps tend to make the most sense where HOV demand is relatively high.

Exhibit V-4
Example of an HOV Drop Ramp

Source: Washington State Department of Transportation, HOV Direct Access Design Guide, Draft, M22-98, April 1998.

Factors to Consider

To accommodate the analysis of HOV drop ramps in Cal-B/C, several factors need to be considered:

- HOV requirement – Like HOV connectors, the HOV occupancy requirement impacts the demand for HOV drop ramps and the size of benefits that accrue on a per-person basis.

- HOV entering and exiting demand – HOV drop ramps serve as the HOV equivalent of on-ramps and off-ramps. The demand for use of drop ramps affects the weaving volume that is avoided by the construction of HOV drop ramps.

- Number of lanes in weaving area – In the absence of HOV drop ramps, entering and exiting HOV traffic must access ramps located near the rightmost lanes of the freeway. This causes a weave section that can be analyzed similar to auxiliary lanes or connectors.

- Number and proximity of interchanges – Like other weave sections, the number and proximity of interchanges affects the length of the weave section and the total weaving volume that it can handle.

- HOV versus non-HOV speeds – In the before case, both HOVs and non-HOVs experience the same diminished speeds in the weaving section. Speeds should improve for both weaving HOVs and non-HOVs that are no long affected by the weave after construction of the drop ramp.

- Accident rate – As with other highway treatments that improve merge conditions, the construction of HOV drop ramps should lower accident rates.

- On-ramps and off-ramps – Providing drop ramps for HOV traffic eliminates the demand for existing on-ramps and off-ramps as HOVs are diverted to the new facilities. If the existing on-ramps or off-ramps were operating near capacity, exiting non-HOVs may experience some benefits as well.

1.5 Off-Ramp Widening

Definition

At some off-ramps, the demand for exiting freeways exceeds the available capacity, causing exiting traffic to backup onto the mainline freeway lanes. One cause may be changing land-uses, such as the construction of a new shopping mall, that lead to increased demand. Another potential cause is the set of local traffic signals at the end of the ramp. The exiting demand may exceed the flow allowed by the timing of these signals.

In both cases, adding lanes to the exit ramp may be warranted. If the issue is due to signal timing, inter-agency coordination may be necessary to change the signal timing or the excess demand need to be handled by on-ramp storage off the mainline freeway system.

Increasing the capacity and storage of off-ramps helps avoid traffic backups onto the mainline freeway lanes and this benefits mainline travelers. The user benefits may be quite large, since mainline lanes can carry large flows relative to the ramps.

However, traffic tends to pre-segregate (i.e., chose lanes) prior to an anticipated congestion point. Through travelers often select left-hand lanes to avoid backups caused by off-ramps.

Factors to Consider

To accommodate the analysis of widening off-ramps in Cal-B/C, several factors need to be considered:

- Exiting vehicle demand – The exiting vehicle demand must be compared to the volume that the off-ramp can handle. If demand exceeds capacity, traffic will back onto the mainline freeway.

- Off-ramp capacity – The number of the lanes on the off-ramp are one determinant of its capacity. However, the ability of the ramp to handle traffic is also affected by design speeds, curvature, and the signal timing of traffic signals at the bottom of the ramp.

- Traffic volume on mainline – Backups caused by inadequate off-ramp capacity impacts mainline traffic, causing delays. The traffic volume measures the number of users potentially impacted.

- Pre-segregation – Travelers in the rightmost lanes of the freeway are the ones most likely to be impacted. If few through travelers remain in the right-hand lanes, then few mainline travelers are impacted.

- Lane changing – If travelers wait to chose an appropriate lane, lane changing to avoided the backup will result in weaving and a reduction in capacity on adjacent lanes.

- Variation in exit demand – If a particular off-ramp frequently experiences heavy queuing, then the regular commutes may anticipate the backups and pre-segregate to avoid the congestion. If the backups are infrequent (such as those at ramps near major sporting events), travelers may not know to pre-segregate and more would be delayed in the right-hand lanes.

- Accident rate – Exit queues that spill onto the mainline freeway are potential safety hazards that could lead to higher accident rates.

1.6 On-Ramp Widening

Definition

As is the case with off-ramps, the demand for on-ramps may exceed available capacity. In some limited circumstances, it may be changing land-uses, such as the construction of a new entertainment center, that lead to increased demand. The Highway Design Manual provides guidance for these situations, suggesting that a two- or three-lane ramp should be provided when volumes exceed 900 vehicles per hour.

However, the more likely scenario is the need for increased storage capacity with the implementation of ramp metering strategies. Metering limits entry of vehicles onto freeways to maintain mainline capacity (which can be lost from access merging). If the demand at a particular ramp exceeds the established metering rate (whether pre-timed or adaptive), traffic will begin to queue behind the ramp meter. Once the queue extends the entire length of the system, the system operator is faced with a dilemma:

- The ramp metering rate can be adjusted to "flush" the queue, which diminishes or eliminates the benefits of the metering strategy, or

- Queues can be allowed to grow, which causes backups or gridlock on the surface street network.

The addition of storage capacity to freeway on-ramps is intended to help eliminate gridlock on surface streets (or the need to conduct inefficient ramp metering).

Factors to Consider

The appropriate factors to consider for analyzing on-ramp widening projects vary depending on the operator-response strategy chosen:

- In the case of queue flushing, Cal-B/C should compare inefficient ramp metering (before condition) with efficient ramp metering (after condition). Task 2 of the Cal-B/C update project addresses the appropriate methodology for analyzing ramp metering.

- In the case of surface street gridlock, Cal-B/C should compare the gridlock conditions with free-flow conditions. For this type of analysis, the model needs to have:

– Total number of vehicles delayed on the surface network – these are the users that benefit from the extra storage capacity on the ramp. Most of these users are on cross-streets or the approach street upstream of the ramp

– Average speed before and after – These speeds are used to calculate travel time savings as well as vehicle operating cost and emission benefits.

– Ramp demand versus metering rate – A portion of the users delayed on the surface network are intending to use the ramp. The benefits for these users are different, because they must still wait in the ramp queue in the after conditions. It is possible that the overall travel time of these users are not impacted by the gridlock, so these users can be ignored in the analysis.

2.0 EXISTING CALTRANS METHODOLOGY

The base version of Cal-B/C is unable to handle any of the operational improvements discussed in this section. Users may be able to simulate the effects of HOV-related projects by adjusting before and after speeds and volumes for HOVs and non-HOVs, but this would be a tedious process and could be subject to capriciousness on the part of the user.

The sections that follow describe some of the other techniques currently used by Caltrans to plan or design operational improvements. Some of these methodologies may be useful for incorporating into Cal-B/C. Methodologies and data sources reviewed include:

- Highway Design Manual
- Ramp Meter Design Manual
- HOV Guidelines Manual
- Safety databases.

2.1 Highway Design Manual

The *Highway Design Manual* establishes uniform policies and procedures for highway design in California. The manual is organized in 25 chapters as shown in Exhibit V-5. Each chapter is updated separately to take into account new design considerations.

Exhibit V-5
California Highway Design Manual Table of Contents

Chapter 500 (last updated November 1, 2001) is directly applicable to the design of operational improvements. It covers the design of traffic interchanges, which the Design Manual defines as:

> *"A combination of ramps and grade separations at the junction of two or more highways for the purpose of reducing or eliminating traffic conflicts, to improve safety, and increase traffic capacity."*

Design Guidance

The Design Manual provides guidance for most of the operational improvements considered in the Cal-B/C update. Some of the most important design considerations are summarized below.

Freeway Interchanges. The Design Manual states that the minimum spacing between interchanges should be 1.5 kilometers (km) in urban areas, 3.0 km in rural areas, and 3.0 km between freeway-to-freeway interchanges and local street interchanges. If interchanges are closely spaced, the manual suggests that the addition of auxiliary lanes, grade-separated ramps, collector distributor roads, and/or ramp metering may be warranted to improve operations.

The Design Manual addresses the importance of minimizing the impacts of weaving. For the design of a freeway-to-freeway interchange, the manual recommends that the design ensures the sign freeway route and major traffic volume be as far left in the traffic lanes as possible to avoid possible conflicts with the interchange. However, the design of these interchanges should balance several factors:

- Cost
- System balance
- Elimination of unnecessary connections
- Servicing local traffic.

Auxiliary Lanes. There are many cases in which the construction of auxiliary lanes is appropriate. The Design Manual states that auxiliary lanes should be provided in all cases where the weaving distance is less than 600 meters. When ramp volumes exceed 1,500 vehicles per hour (vph), the Design Manual recommends providing an auxiliary lane with a minimum length of 300 meters. An auxiliary lane approximately 400 meters long should be provided in advance of a two-lane exit. The manual provides other auxiliary lane lengths for special circumstances, such as branch merges and diverging connections. Gradients and truck volumes may warrant longer auxiliary lanes. Also, close proximity of interchanges may warrant conducting weaving analyses to determine whether extending the ramp lane transition is necessary.

HOV Drop Ramps and Direct Connectors. As a basic policy, all freeway entrances and exits, except for direct connections with median HOV lanes, should connect to the right of through traffic. The HOV Guidelines provide additional information specific to direct connections to HOV lanes.

Ramp Storage. The ramp meter system should provide adequate storage for queues. To minimize the impact on local streets, ramp designers should make every effort possible to meet the recommended storage length. Wherever feasible, ramp metering storage should be contained on the ramp by either widening or lengthening it.

The Design Manual states that the District Operations Branch responsible for ramp metering must be consulted to determine the desirable ramp meter storage. In designing ramps to accommodate ramp metering, the ramp design for new facilities should be based upon the peak-hour traffic volumes projected for 20 years after completion of construction. The ramp designs to accommodate ramp meters should be based on current (less than two years old) peak-hour traffic volume. A minimum vehicle spacing of nine meters should be used for designing storage on metered ramps.

Ramp meters have practical lower and upper output limits of 240 and 900 vph per lane. A single-lane ramp meter is appropriate for volumes up to 900 vph. When entrance ramp volumes exceed 900 vph, or when an HOV lane is to be provided, the ramp segment should contain two or three lanes. Two-lane meters may be appropriate even

when ramp volumes are between 500 and 900 vph. Three-lane metered ramps are typically needed to serve peak-hour traffic in urban and suburban freeway corridors.

Improvements to the local street system in the vicinity of the ramp should also be considered where there is insufficient storage length on the ramp and the ramp queue will adversely affect local streets. Local street improvements can include widening, re-striping, or timing signals. All of these improvements require coordination with local agencies.

Weaving Analysis

The Highway Design Manual provides guidance on methods to use for analyzing the capacity and operating characteristics of weaving sections. The Design Manual describes a weaving section as:

> *"A length of one-way roadway where vehicles are crossing paths, changing lanes, or merging with through traffic as they enter or exit a freeway or collector-distributor road."*

The manual makes a distinction between single weaving sections and multiple weaving sections. A single weaving section has an inlet upstream and an exit downstream of the weaving section. A multiple weaving section is characterized by more than one ingress followed by one or more points of egress.

The Highway Design Manual provides a very rough guide for designing the length of weave sections. Approximately a Level of Service (LOS) C is provided if the weaving section is 0.3 meters long for every weaving vehicle per hour. Weaving sections in urban areas should be designed for LOS C or D, while weaving sections in rural areas should be designed for LOS B or C. The January 31, 1995 Design Information Bulletin Number 77 on Interchange Spacing provides additional information on weaving requirements.

As described in Section 5 (Recent Research and Findings) of this report, a number of methods have been developed to analyze the capacity of weaving sections and this research continues. The Design Manual states that only two methods are authorized for conducting capacity analyses for weaving sections on California highways:

- Leisch Method
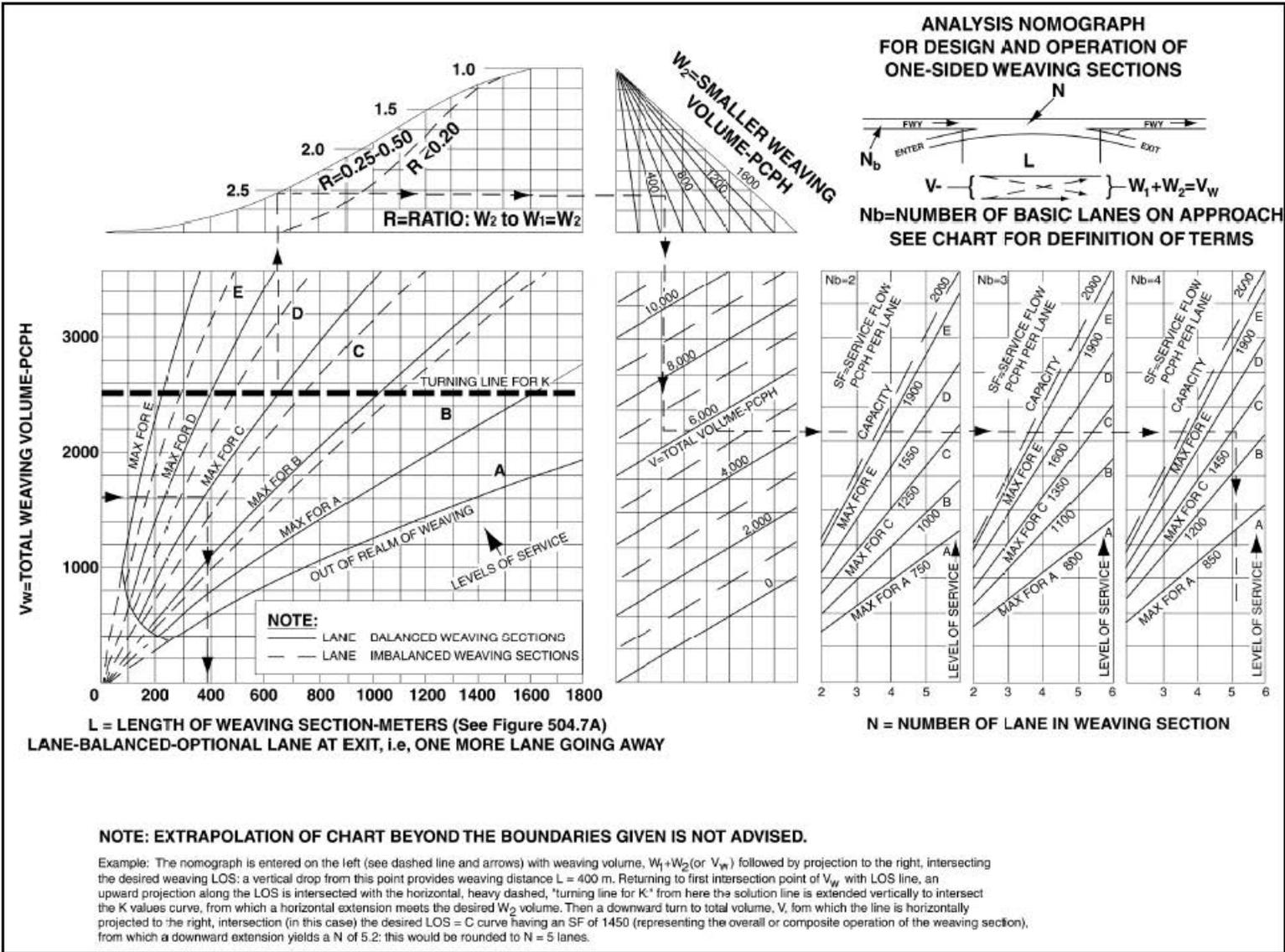- Level of Service D Method.

The Design Manual cautions that other methods may not provide accurate results. The manual specifically mentions the 1994 Highway Capacity Manual (HCM) method. This method has been modified slightly for the HCM 2000.

The federal government uses the HCM 2000 method to analyze projects. In August 2001, the Federal Highway Administration (FHWA) established a policy that requests for access points to the Interstate System for all new studies beginning after October 1, 2001 should use the HCM 2000 analysis procedure. Further clarification of the policy allows Caltrans to use any traffic analyses methods it chooses (i.e., those specified in the Design Manual), but the FHWA requests that raw data be submitted with the requests so results can be analyzed independently using HCM 2000 methods.

A description of the two methods, as documented in the Highway Design Manual, follows. The manual recommends checking the result obtained using the Leisch Method with the Level D Method if the weaving section has a single-lane ramp, an auxiliary lane, and weaving rates exceeding 2500 passenger car equivalents per hour (PCEPH). As described in Section 5, recent research at the University of California at Berkeley (UCB) suggests that a modified Level D Method could also be used for major weaving sections (with entry and exit on opposite sides of the freeway).

Leisch Method. Jack Leisch and Associates developed this method to determine the length of weaving sections for freeways and collector-distributor roads. Exhibit V-6 provides the appropriate Leisch chart for determining the level of service in a weaving section. The analysis in the first panel on the lower left of the chart. The analyst must determine whether the weaving section is "balanced" or "unbalanced" by matching the particular freeway design to the schematics provided in Exhibit V-7. The level of service for the total volume over all lanes of the weaving section is then found from the panels on the right of the chart in Exhibit V-6. Design rates for lane balanced weaving sections where at least one ramp or connector has two lanes should result in a service level at least in the middle of LOS D category. The weaving length should not be less than 500 meters on main freeway lanes except in cases with excessive cost or environmental constrains. For each additional lane to be crossed by weaving vehicles, 300 meters should be added to the weaving length. The Design Manual cautions that the weaving chart should not be extrapolated beyond the curves shown.

ANALYSIS NOMOGRAPH FOR DESIGN AND OPERATION OF ONE-SIDED WEAVING SECTIONS

Nb=NUMBER OF BASIC LANES ON APPROACH
SEE CHART FOR DEFINITION OF TERMS

L = LENGTH OF WEAVING SECTION-METERS (See Figure 504.7A)
LANE-BALANCED-OPTIONAL LANE AT EXIT, i.e, ONE MORE LANE GOING AWAY

N = NUMBER OF LANE IN WEAVING SECTION

NOTE: EXTRAPOLATION OF CHART BEYOND THE BOUNDARIES GIVEN IS NOT ADVISED.

Example: The nomograph is entered on the left (see dashed line and arrows) with weaving volume, W_1+W_2 (or V_w) followed by projection to the right, intersecting the desired weaving LOS: a vertical drop from this point provides weaving distance L = 400 m. Returning to first intersection point of V_w with LOS line, an upward projection along the LOS is intersected with the horizontal, heavy dashed, "turning line for K" from here the solution line is extended vertically to intersect the K values curve, from which a horizontal extension meets the desired W_2 volume. Then a downward turn to total volume, V, fom which the line is horizontally projected to the right, intersection (in this case) the desired LOS = C curve having an SF of 1450 (representing the overall or composite operation of the weaving section), from which a downward extension yields a N of 5.2: this would be rounded to N = 5 lanes.

Source: California Highway Design Manual, November 1, 2001, p. 500-40.

Operational Improvements

Source: California Highway Design Manual, November 1, 2001, p. 500-41.

V-19

System Metrics Group, Inc.

Exhibit V-7
Lane Configuration of Weaving Sections

Cal-B/C Technical Supplement Volume 2
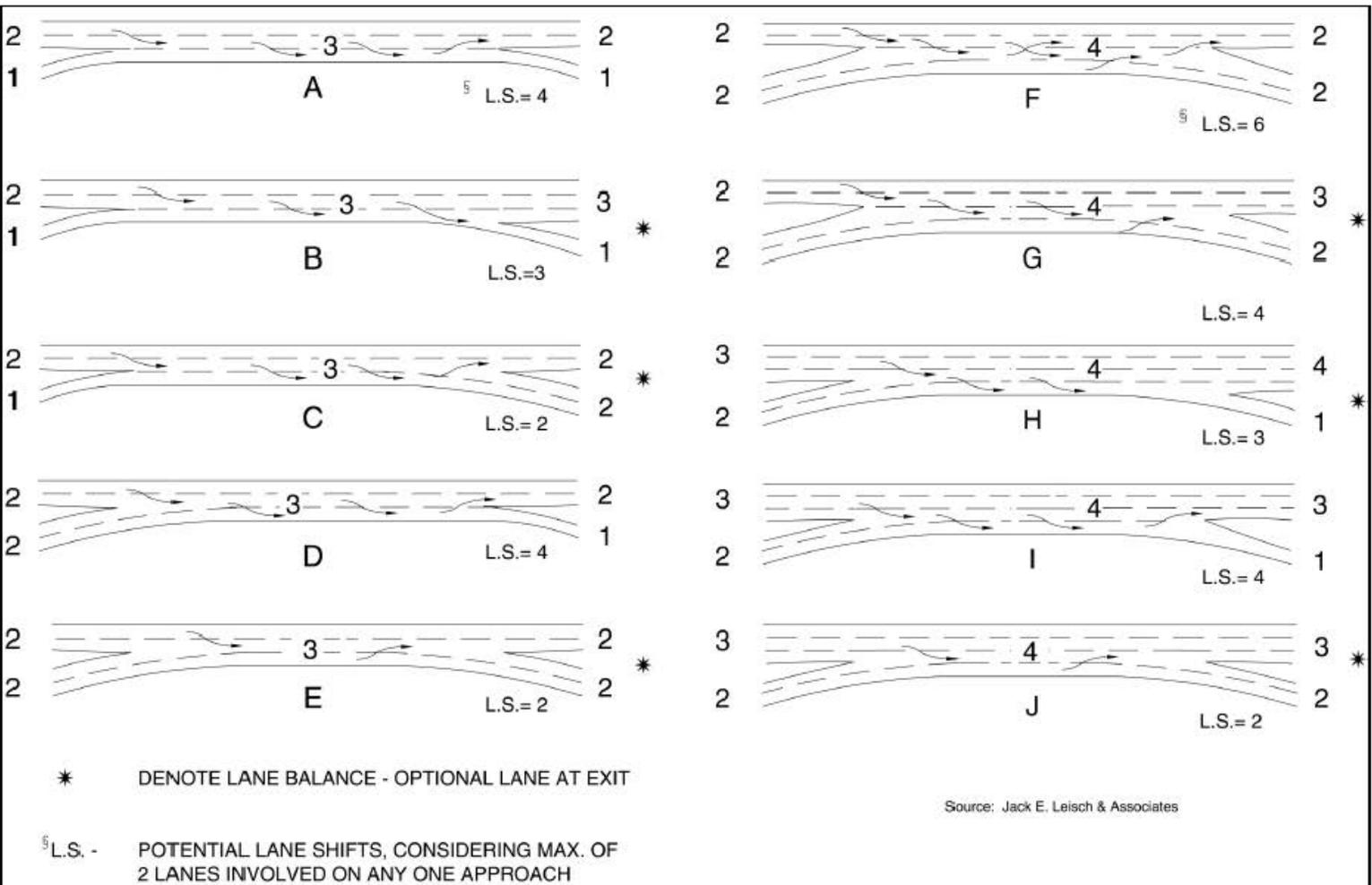
Level D Method. This method was provided in the 1965 Highway Capacity Manual (pages 234 to 238) to provide a method for determining the adequacy of weaving sections near single-lane ramps. It is also documented in Caltrans Traffic Bulletin 4, which is available from the Division of Traffic Operations. The Level D method can be used to project volumes along a weaving section and compare these volumes to capacity. The Design Manual includes two exhibits reprinted from the HCM 1965. Exhibit V-8 estimates the approximate amount of through traffic that remains in the rightmost lane near a ramp terminal, depending on the highway geometrics. Exhibit V-9 provides an equivalent graph for ramp traffic merging. According to the Design Manual, volumes in PCEPH should be adjusted to account for freeway grades and truck volumes. Exhibit V-10 illustrates the use of the chart contained in Exhibit V-8.

Exhibit V-8
Percent of Through Traffic Remaining in Outer Through Lane
(Level of Service D Procedure)

TOTAL VOLUME OF THROUGH TRAFFIC, ONE DIRECTION (vph)	APPROXIMATE PERCENTAGE OF THROUGH[a] TRAFFIC REMAINING IN THE OUTER THROUGH LANE IN THE VICINITY OF RAMP TERMINALS AT LEVEL OF SERVICE D.		
	8-LANE[b] FREEWAY	6-LANE[c] FREEWAY	4-LANE[d] FREEWAY
6500 and over	10	-	-
6000 - 6499	10	-	-
5500 - 5999	10	-	-
5000 - 5499	9	-	-
4500 - 4999	9	18	-
4000 - 4499	8	14	-
3500 - 3999	8	10	-
3000 - 3499	8	6	40
2500 - 2999	8	6	35
2000 - 2499	8	6	30
1500 - 1999	8	6	25
Up to 1499	8	6	20

a. Traffic not involved in a ramp movement within 1200 m in either direction.
b. 4 lanes one way
c. 3 lanes one way
d. 2 lanes one way

Source: California Highway Design Manual, November 1, 2001, p. 500-42.

Exhibit V-9
Percentage of Ramp Traffic in the Outer Through Lane
with No Auxiliary Lane
(Level of Service D Procedure)
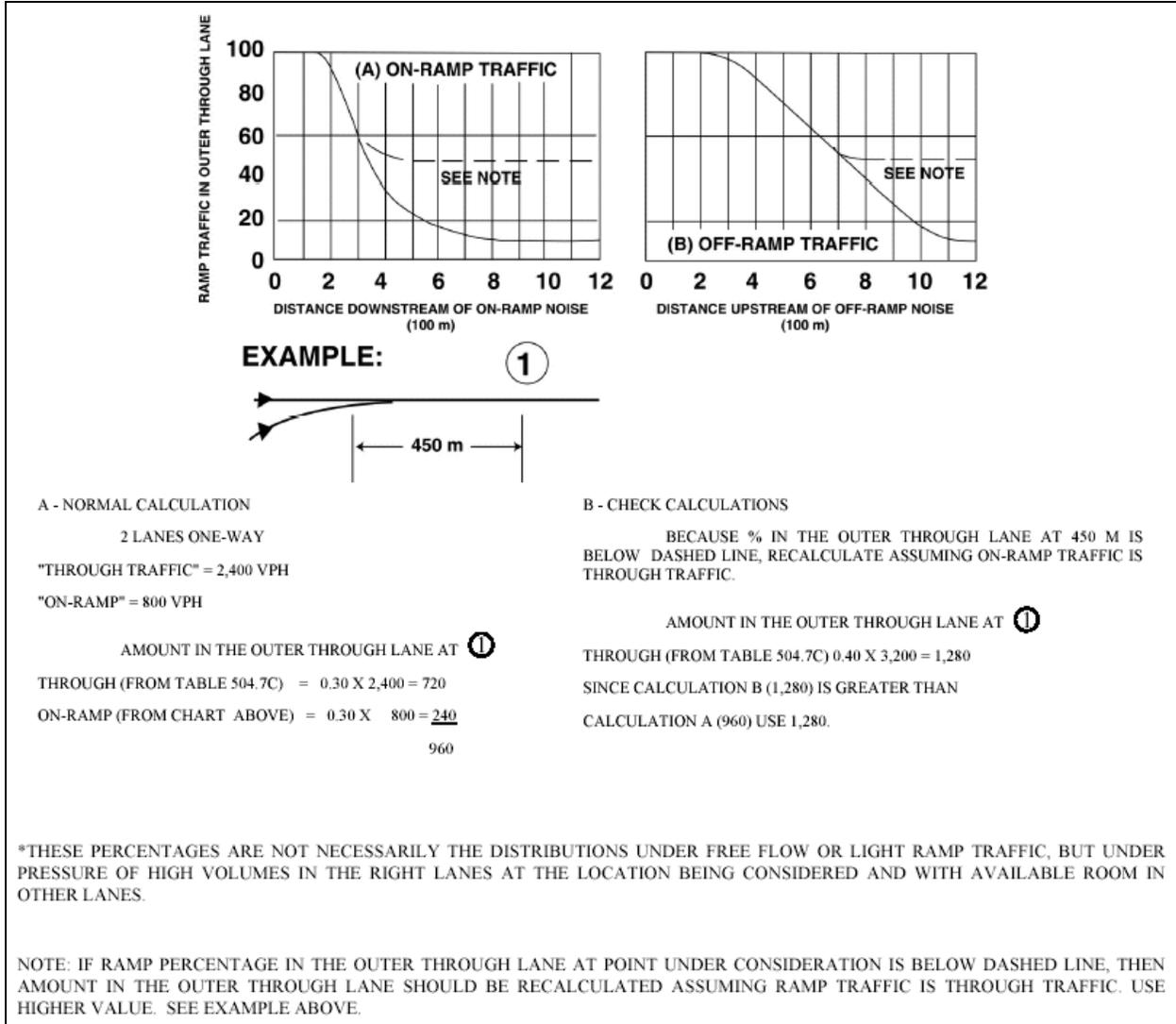
Source: California Highway Design Manual, November 1, 2001, p. 500-44.

Exhibit V-10
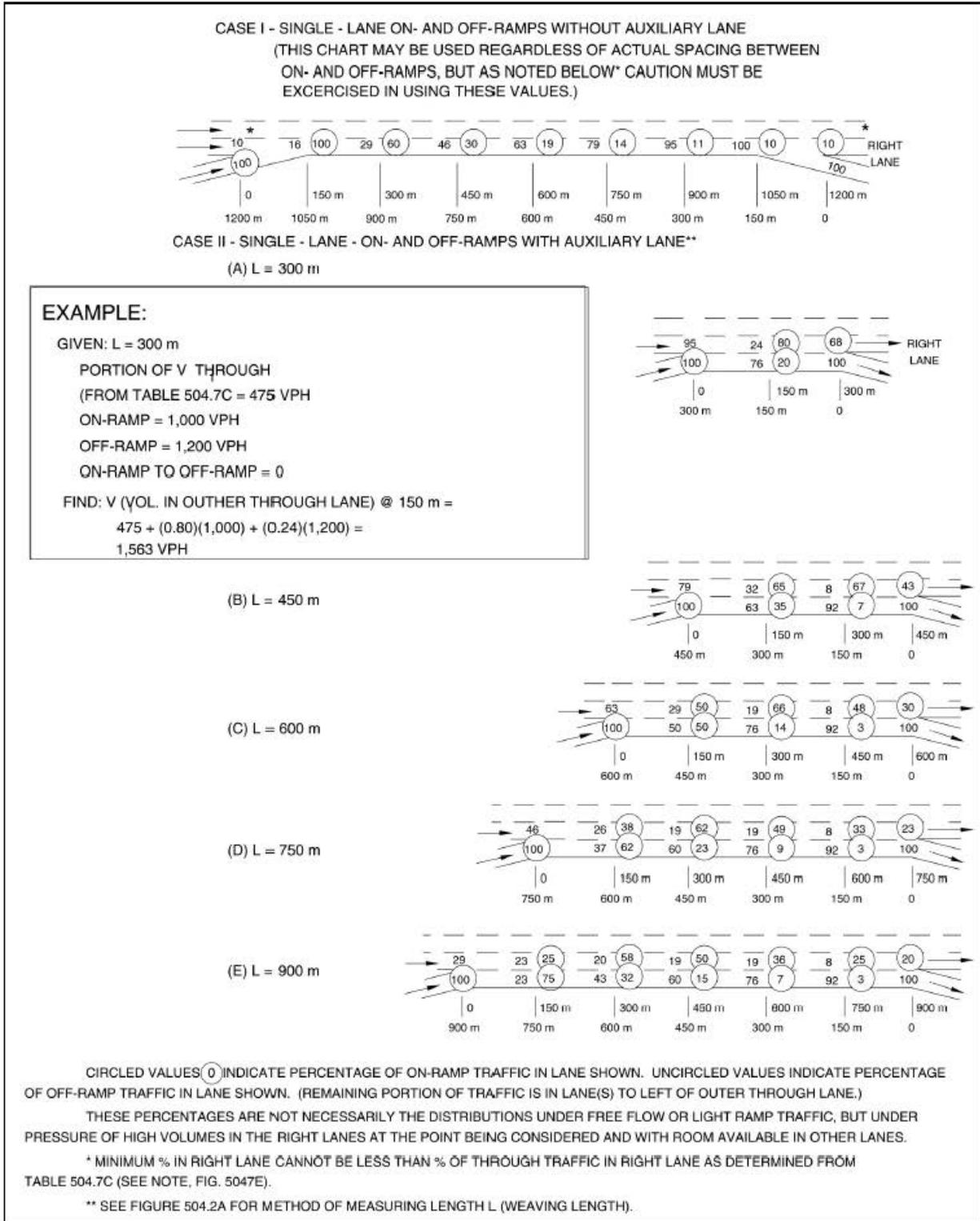## Percentage Distribution of On- and Off-Ramp Traffic
in Outer Through Lane and Auxiliary Lane
(Level of Service D Procedure)

CASE I - SINGLE - LANE ON- AND OFF-RAMPS WITHOUT AUXILIARY LANE
(THIS CHART MAY BE USED REGARDLESS OF ACTUAL SPACING BETWEEN
ON- AND OFF-RAMPS, BUT AS NOTED BELOW* CAUTION MUST BE
EXCERCISED IN USING THESE VALUES.)

CASE II - SINGLE - LANE - ON- AND OFF-RAMPS WITH AUXILIARY LANE**

(A) L = 300 m

EXAMPLE:

GIVEN: L = 300 m

PORTION OF V THROUGH
(FROM TABLE 504.7C = 475 VPH
ON-RAMP = 1,000 VPH
OFF-RAMP = 1,200 VPH
ON-RAMP TO OFF-RAMP = 0

FIND: V (VOL. IN OUTHER THROUGH LANE) @ 150 m =

$$475 + (0.80)(1,000) + (0.24)(1,200) = 1,563 \text{ VPH}$$

(B) L = 450 m

(C) L = 600 m

(D) L = 750 m

(E) L = 900 m

CIRCLED VALUES ⓪ INDICATE PERCENTAGE OF ON-RAMP TRAFFIC IN LANE SHOWN. UNCIRCLED VALUES INDICATE PERCENTAGE OF OFF-RAMP TRAFFIC IN LANE SHOWN. (REMAINING PORTION OF TRAFFIC IS IN LANE(S) TO LEFT OF OUTER THROUGH LANE.)

THESE PERCENTAGES ARE NOT NECESSARILY THE DISTRIBUTIONS UNDER FREE FLOW OR LIGHT RAMP TRAFFIC, BUT UNDER PRESSURE OF HIGH VOLUMES IN THE RIGHT LANES AT THE POINT BEING CONSIDERED AND WITH ROOM AVAILABLE IN OTHER LANES.

* MINIMUM % IN RIGHT LANE CANNOT BE LESS THAN % OF THROUGH TRAFFIC IN RIGHT LANE AS DETERMINED FROM TABLE 504.7C (SEE NOTE, FIG. 5047E).

** SEE FIGURE 504.2A FOR METHOD OF MEASURING LENGTH L (WEAVING LENGTH).

Source: California Highway Design Manual, November 1, 2001, p. 500-43.

2.2 Ramp Meter Design Manual

Caltrans developed the *Ramp Meter Design Manual* to provide designers, consultants, and local agencies that perform design work on State highways, a document that addresses the policies, design standards, and practices for the design and operation of new or existing ramp meters. It includes discussions of the design of metered ramps, ramp meter hardware necessary, and signing and pavement markings. The manual provides guidance for the analysis of on-ramp storage capacity and off-ramp capacity.

The manual recommends that geometric ramp design for new facilities should be based on projected peak-hour traffic volumes 20 years after completion of construction and operational improvement projects should be based on current peak-hour traffic volumes (less than two years old). If ramp volumes are less than 900 vph, a single-lane design can be used. When volumes exceed 900 vph, a two- or three-lane ramp should be provided. If truck volumes exceed five percent with an ascending ramp of three percent or ramp volumes exceed 1,500 vph, auxiliary lanes should be provided beyond the ramp convergence point.

Providing adequate queue storage is also an important design consideration. Ramp meter flow rates typically range from 240 to 900 vph. Ramp meter storage should be contained on the ramp through widening or lengthening if necessary. The manual states that an HOV preferential lane shall be provided at all ramp meter locations. Enforcement and operations/maintenance pullout areas should also be provided.

One of the appendices includes a method for estimating the maximum queue, total delay, total vehicles delayed, and average delay using an arrival discharge chart.

Each District is responsible for preparing a Ramp Meter Development Plan (RMDP) identifying the freeway segments that are expected to be metered within the next ten years. In addition, existing interchange modification and new interchange projects should include provisions for ramp meters.

2.3 HOV Guidelines Manual

The HOV Guidelines Manual provides planners, designers and operators with policies, design standards, and practices for the deployment of mainline HOV facilities. The guidelines are intended to be advisory in nature and used only when every effort to conform to established standards has been exhausted. The manual includes six sections coveting: planning, operations, geometric design, ingress/egress, signing and delineation, and enforcement. The appendix contains statues and policies relevant to HOV facilities.

HOV Direct Connectors. The guidelines were last updated in 1991. At that time, operational experience with HOV direct connectors was limited, but the manual offers some factors that should be analyzed when director connectors are considered:

- Will the direct connector provide HOV system continuity and will it be an integral element of the overall HOV system?

- Is forecasted HOV peak-hour volume for the connector greater than 500 vehicles per hour per lane (vphpl) or 1100 persons per hour per lane within five years from opening? If not, will space be provided in the interchange for the eventual construction of direct connectors?

- If the alternative to direct connectors are weaving movements across mixed-flow traffic, will a weaving analysis show the development of a major bottleneck, resulting in a net loss in overall time savings? If so, this situation may justify building HOV connectors, particularly if the bus volume is high.

- Although direct connectors should not be categorically rejected because of cost, will the benefit/cost analysis imply a reasonable rate of return?

- Will the community accept the additional structural height which may be necessary for direct connectors?

- Is there a plan to maintain a desirable level of service for the HOV traffic by: 1) converting to a higher occupancy requirement, or 2) providing an additional HOV lane to maintain a desirable level of service for the HOV traffic?

- Will it be fundable? Typically, much of a direct connector is a structure. Care must be taken when planning and funding an HOV system so that expensive direct connectors do not prevent large portions of the system from being built.

- With regard to the buffer-separated or barrier-separated HOV facility, would an additional ingress point be impractical due to the high cost of providing lateral space in the median?[19]

The HOV Guidelines list anticipated benefits of direct connectors as: 1) net travel time savings, and 2) safety benefits when compared to a ground-level merging maneuver. The guideline notes that travel time savings must consider the potential increase in delay for mixed-flow traffic. Since HOV facilities are intended to increase vehicle occupancy, time savings may be based on a per-user basis rather than a per-vehicle basis. The guidelines state that safety benefits for direct connectors are difficult to

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[19] *California Department of Transportation, High Occupancy Vehicle (HOV) Guidelines for Planning, Design, and Operations, July 1991, pp. 3-13 to 3-14.*

evaluate and should be discussed qualitatively until there is sufficient operational experience.

The Guidelines state that HOV direct connectors should be built to freeway connector standards, except for 4-foot left shoulders. HOV connectors may merge or diverge from either side of through HOV lanes.

HOV Drop Ramps. The HOV Guidelines note that operational data for HOV drop ramps were lacking at the time the guidelines were written. The manual recommends that the following factors be considered until more data become available:

- Does the benefit/cost analysis regarding time savings and safety benefits indicate a reasonable rate of return?

- Is there a high concentration of HOV demand due to major attractions such as transit facilities, park and ride facilities, central business districts, or industrial concentrations?

- Are HOV volumes using the interchange large enough to have a significant negative impact on the through traffic lanes due to weaving maneuvers?

- Does removal of HOV traffic improve the operating level of service for the freeway, the interchange, or the cross streets?[20]

HOV connectors and drop ramps have not been widely deployed nationally, since they are applicable only to areas with fairly large HOV networks. Several states (including California and Washington) are beginning to address HOV drop ramps and connectors in their design manuals.

California has already deployed some HOV drop ramps and connectors and more are planned. It is worth noting the size of California's HOV network to understand why connectors and drop ramps have become important elements to assess in Cal-B/C.

There were an estimated 2500 lane-miles of HOV facilities in the United States in 2001.[21] California alone accounted for 1060 lane-miles, or over 40 percent of HOV facilities nationally. The majority of these facilities are located in Southern California (including Los Angeles, Ventura, Orange, San Bernardino, and Riverside counties), which contained 769 HOV line-miles.[22]

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[20] *California Department of Transportation, High Occupancy Vehicle (HOV) Guidelines for Planning, Design, and Operations, July 1991, pp. 3-13 to 3-16.*

[21] *Fuhs, Charles and Obenberger, Jon, HOV Facility Development: A Review of National Trends, 2001, p. 26.*

[22] *California Department of Transportation, 2001 HOV Annual Report: District 7, May 2002, p. 3.*

With nearly 30 percent of the HOV lanes in the United States, Southern California has a very large network that can take advantage of user the benefits provided by HOV connectors and drop ramps. A number of these facilities have been built in Orange County (Exhibit V-11) and several more are planned for Southern California (Exhibit V-12). Northern California is also planning facilities, with three HOV connectors currently programmed using local funds in Santa Clara County.[23]

Exhibit V-11
HOV Connector and Drop Ramp
Locations in Orange County as of 2001

Source: California Department of Transportation, 2001 District 12 Annual HOV Report, May 2002.

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[23] *California Department of Transportation, 2001 District 4 HOV Report, February 2002, p. 13.*

Exhibit V-12
Status of Southern California HOV System in 2001

Source: California Department of Transportation, 2001 HOV Annual Report:
District 7, May 2002

2.4   Safety Databases

The Statewide Integrated Traffic Records System (SWITRS) is a statewide records system with data for fatal and injury motor vehicle traffic accidents. A large proportion of the reported property damage only (PDO) accidents are also entered into the SWITRS database. Reports are generated by over 100 CHP areas and over 500 city police departments, sheriffs offices and other local jurisdictions.

Caltrans receives on a weekly basis a subset of SWITRS data for collisions occurring on State Highway for the Traffic Accident Surveillance and Analysis System (TASAS). Additional information is added about the objects struck and detailed locations. TASAS has an accident database linked to a highway database, which contains description elements of highway segments, intersections and ramps, access control, traffic volumes and other data.

Caltrans produces an annual report entitled "Accident Data on California State Highways (Road Miles, Travel, Accidents, Accident Rates," which provides summary information from the SWITRS and TASAS databases. The report contains accident rate data for several facility types and is frequently the source of before and after accident data (by facility type) provided by analysts using the current Cal-B/C model.

Accident rates for some of the operational improvements discussed in this task report are included under the ramp facility type (as listed in the annual Caltrans report):

- On- and off-ramps
- Diamond (HOV) ramps
- Direct and semi-direct connectors.

Statewide-average accident rates are provided neither for auxiliary lanes nor for HOV connectors, so it is difficult to assess the safety impacts of improvements on these facilities. Also, the accident rates for ramps are not separated by the number of lanes on the facility.

3.0   OTHER METHODOLOGIES

The next few sections describe how computerized models handle the impact of operational improvements on user benefits:

- FREQ
- FRELANE
- INTRAS (INtegrated TRaffic Simulator)
- SCReening Analysis for ITS (SCRITS)
- Highway Economic Requirements System (HERS)
- Surface Transportation Efficiency Analysis Model (STEAM)
- American Association of State Highway and Transportation Officials (AASHTO) Redbook.

3.1   FREQ

Over the last twenty years, researchers at the Institute of Transportation Studies at the UCB have developed a series of freeway corridor simulation models (called FREQ) for the evaluation of various design and operational improvements. Dolf May, who participated in several of the weaving analysis studies at UCB, is the lead developer of FREQ.

FREQ is a PC-based system of macroscopic freeway corridor simulation models. It can analyze a variety of freeway conditions, including HOV facilities, ramp control optimization, normal and priority entry control, time-varying reconstruction activities and freeway incidents, geometric changes, freeway-arterial diversion, future growth scenarios, and advanced transportation management information systems (ATMIS) combinations. The analysis includes traffic simulation, modeling of traveler responses, and calculation of measures of effectiveness.

FREQ12 is the latest version of FREQ. For this version, the program is rewritten to run as a Windows application with new features to simplify data entry. The speed-flow relationships in the model are updated to include those in the 2000 Highway Capacity Manual. The program includes a graphical interface with input checking, default values, graphic representation of the simulation results, and user-selected output options including traffic performance contour maps.

FREQ12 contains two models:

- *FREQ12PE*, an entry-control macroscopic model for analyzing ramp metering

- *FREQ12PL*, a freeway priority macroscopic model for analyzing HOV facilities.

FREQ12 can analyze a one-directional freeway corridor that can include an arterial or group of "bundled" arterials. The model can handle approximately 50 to 100 miles of freeway corridor with a maximum of 158 subsections,78 origins, and 78 destinations.

The model analyzes weaving sections by reducing the capacity of the corridor. FREQ uses the Level D methodology from the 1965 Highway Capacity Manual. This is the same weaving analysis methodology recommended in the Caltrans Design Manual. The model also includes discrete choice theory developed by McFadden[24] to predict the percentage of travelers on a freeway that would switch modes given certain conditions. Discrete choice theory is used to analyze the likely effects of adding high-occupancy vehicle lanes and ramp metering.

The model is currently used in nine Caltrans districts as part of the freeway operations training program.

3.2   FRELANE

The FRELANE Analysis Model was developed at UCB to analyzing major weave sections and selected freeway segments.

Between 1987 and 1989, researchers at UCB conducted a two-year study on major freeway weave sections, such as those near freeway interchanges. The research culminated in a new technique for analyzing major freeway weave sections, such as those near freeway interchanges. The research is summarized in Cassidy, Chan, Robinson, and May (1990). It is also described further in Section 5 on Recent Research.

The technique developed during the research was computerized and the resulting model was called FREWEV. Subsequent research by Robinson, Vandehey, Mazur, and May (1992) developed point-flow prediction methods to analyze additional segments of the freeway. FRELANE implements the prediction methods developed in this research and incorporates the prior FREWEV model.

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[24] *Daniel L. McFadden won the Nobel Prize in Economics for discrete choice theory.*

FRELANE is a PC-based program for designing and analyzing eight different types of freeway segments

- Major weave (four types)
- Simple weave with an auxiliary lane
- On-off without an auxiliary lane
- Straight pipe
- Isolated on
- Isolated off
- On-on
- Multiple weave (one type).

FRELANE enables the user to select one of the eight freeway segments, enter input data on graphic screens of that segment, and analyze the freeway section using a total point-flow prediction method.

FRELANE can be run in two different modes. The Empirical mode analyzes only sections that adhere to the design and demand values for which empirical data are available. The Empirical and Simulation mode allows the program to include freeway sections for which empirical data are not available. The data for such sections are generated through simulation runs.

The model calculates values at up to seven points along the section. Output includes the total point flow at each of the analysis points, the point flow by movement at each analysis point, and the amount of traffic crossing the lane boundaries in the conflict area computed between each of the analysis points.

3.3   INTRAS (INtegrated TRaffic Simulator)

INTRAS (INtegrated TRaffic Simulator) is a microscopic freeway simulation program developed by KLD Associates for FHWA to model the movement of traffic on freeways, ramps, and adjacent surface streets. The program was original developed in the late 1970's to assess the effectiveness of ramp metering and incident management strategies.

It has been used for the last decade to predict flows and lane-changing rates within a weaving section. The model simulates the movement of individual vehicles on a freeway and surface street network using a series of car-following, lane-changing, and queue discharge algorithms.

INRAS was succeeded by FRESIM, which is now incorporated into CORSIM. CORSIM is part of the Traffic Software Integrated System (TSIS) collection of software tools maintained by FHWA. CORSIM is a comprehensive microscopic traffic simulation, applicable to surface streets, freeways, and integrated networks and allows the addition of control devices (such as traffic signals and ramp metering). CORSIM simulates

traffic and traffic control systems using commonly accepted vehicle and driver behavior models.

3.4   SCReening Analysis for ITS (SCRITS)

SCReening Analysis for ITS (SCRITS) is a sketch-planning tool tailored for preliminary, "early-stage" analyses of ITS benefits. It can be employed in a focused ITS analysis, a corridor/sub-area transportation study, or within the context of a regional planning analysis. SCRITS is structured as an Excel worksheet that comprises baseline data, a total of 16 ITS components, and lookup tables of values that are used to generate output calculations. The format is designed to allow users to include additional ITS applications, perform different calculations, and modify existing formulas and lookup tables. It also offers flexibility in terms of geographic and facility coverage, provided that the user supplies baseline data that are consistent with the coverage analyzed.

SCRITS does not support the analysis of any of operational improvements considered for inclusion in Cal-B/C. However, it does include a number of the ITS improvements considered in the update. SCRITS is described further in the Deliverable 2b report that covers models applicable to ITS improvements.

3.5   Highway Economic Requirements System (HERS)

The FHWA developed the Highway Economic Requirements System (HERS) model to predict the investment required to achieve certain highway system performance levels. HERS applies engineering standards to identify highway deficiencies and applies economic criteria to select the most cost-effective mix of highway system improvements. HERS considers capital improvement projects directed at correcting pavement and/or capacity deficiencies. Output of the HERS model is used in the Department of Transportation's *Status of the Nation's Surface Transportation System – Condition and Performance – Report to Congress*, which is produced biennially.

HERS estimates the benefits to highway users (travel time, operating costs, and safety), to highway agencies (maintenance costs and the residual value of an improvement at the end of the analysis period), and reduction in vehicle emissions. A benefit-cost analysis is used to compare potential improvements. For each funding period, HERS forecasts the condition of each sample section and determines which improvements should be made. The current version of the HERS model considers highway improvements to the pavement (resurfacing and reconstruction) and geometrics (lane widening and additions; shoulder improvements; curve and grade improvements; and access control and median improvements for urban freeways).

HERS cannot estimate directly the benefits of the operational improvements proposed for inclusion in Cal-B/C. However, HERS can be used to estimate the effects of improvements that affect capacity by using a pair of runs with the "with" and

"without" capacities provided by the users. The user would have to determine these capacities outside the model.

3.6   Surface Transportation Efficiency Analysis Module (STEAM)

The FHWA developed the Surface Transportation Efficiency Analysis Model (STEAM) in 1997 to allow for detailed comparison of proposed transportation solutions in corridor and system-wide analysis. The STEAM model builds upon a corridor sketch planning tool called the Sketch Planning Analysis Spreadsheet Model (SPASM), developed by DeCorla-Souza, Cohen and Bhatt for the FHWA in 1995. SPASM was intended to assist planners in developing economic efficiency and other evaluative information needed for comparing cross-modal and demand management strategies.

STEAM imports outputs from four-step travel demand models and post-processes traffic assignment volumes to derive highway travel speeds that are sensitive to congestion and queuing impacts. STEAM estimates the impacts of transportation investments and policies, including major capital projects, pricing, and travel demand management (TDM). Quantitative estimates of resource usage and environmental impacts such as energy consumption and pollutant emissions are provided. In addition, impacts are monetized to provide an estimate of net monetary benefits or costs of alternatives to evaluate trade-offs against non-monetizable impacts. STEAM applies consumer surplus theory to estimate the user benefits of alternative programs and policies.

Released in 2000, STEAM 2.0 is the latest version of the software. It reports mobility and safety benefits by user-defined districts as well as accessibility. The district-level reporting feature allows users to compare the impacts of transportation investments to resident trip-makers across aggregations of zones, which may represent neighborhoods, policy areas or political jurisdictions. The accessibility feature produces estimates of employment opportunities within a user-defined travel-time threshold of a district across a base and improvement scenario.

STEAM 2.0 is flexible in terms of the user's definition of travel markets. Default analysis parameters exist for seven modes, including: auto, truck, carpool, local bus, express bus, light rail, and heavy rail. Users can specify different values of time for different travel markets, and they are asked to provide "base case" and "improvement case" trip tables for different trip purposes. STEAM 2.0 can be applied to average weekday traffic or to peak and off-peak traffic with different definitions of the peak periods.

STEAM 2.0 provides estimates for the following:

- Benefits and costs to transportation users
- Annualized costs to public agencies
- Effects on total transportation cost

- Changes in accessibility to jobs for residents of defined districts.
- Changes in emissions for particular, hydrocarbons, carbon monoxide, and nitrogen oxides
- Changes in energy use
- Changes in noise and other external costs
- Changes in fatal, injury, and property damage only accidents
- Revenue transfers due to toll or fare changes.

STEAM 2.0 cannot estimate directly the benefits of the operational improvements proposed for inclusion in Cal-B/C. The new version of the software does contain a capacity analysis feature with equations to calculate peak, off-peak, and average weekday speeds for freeways and arterials as a function of: 1) free-flow speed, 2) average weekday traffic, and 3) capacity (in vehicles per hour). However, the model does not adjust the capacity in these equations automatically to account for increases due to operational improvements. The user would have to conduct the capacity analyses outside STEAM and feed the results into STEAM using the user-defined trip tables by origin-destination zone for before and after scenarios. STEAM could then calculate the system-wide impact of the capacity improvements.

3.7 American Association of State Highway and Transportation Officials (AASHTO) Redbook

In 1977, AASHTO published *A Manual on User Benefits Analysis of Highway and Bus-Transit Improvement*. This publication, commonly referred to as the "Redbook," has become a standard reference for evaluating user benefits arising from highway and transit improvements.

The National Academy of Sciences has recently contracted to update the highway portion of the Redbook under NCHRP Project 02-23. The final product will be a manual entitled *User Benefit Analysis for Freeways*. Although the final manual has not yet been published, a draft version dated September 2002 is available.

The draft manual provides a comprehensive methodology for evaluating user benefits from highway improvements. The manual discusses a number of technical issues, such as monetizing benefits, selecting discount rates, and estimating specific user benefits.

The report discusses the analysis of a broad range of highway improvements:

- Development of new roads
- Operational improvements to existing roads (includes traffic control, signal systems, ITS improvements, and pricing and regulatory policies)
- Safety improvements to existing roadways (includes geometric improvements, lane improvements, access management, and roadside improvements)
- Highway project-management activities.

Under a section describing the analysis of ramp metering, the new Redbook recommends modeling the improvement by its impact on traffic behavior in merge influence areas. The manual explains that the HCM 2000 provides empirical relationships between traffic volumes and density in the merge influence area. These relationships permit the calculation of freeway travel times as a function of the floes in the two rightmost freeway lanes approaching the merge area and the on-flow from the ramp.

While the HCM provides detailed procedures for estimating the approaching traffic flows in the two rightmost lanes, the Redbook recommends that per-lane traffic volumes can be prorated since the analysis is conducted for sketch purposes. Prorating exaggerates the delays associated with merging, but the Redbook suggests that this is a useful bias in the analysis of turbulent traffic.

The manual provides an equation to use for saturated conditions and notes that speeds would be lower under unsaturated conditions:

$$S_{merge} = \frac{V_{merge}}{D_R} \leq \frac{(V_{12} + V_R)}{(5.475 + 0.00734 V_R + 0.0078 V_{12} - 0.00627 L_A)}$$

where,

S_{merge} = the speed in the merge influence area (mph)
V_{merge} = the total volume of traffic in the merge influence area (vehicles/hour)
D_R = the density of vehicles in the merge influence area (vehicles/mile/lane)
L_A = the length of the acceleration lane (miles)
V_{12} = the traffic flow entering the merge area in the first two lanes
V_R = the peak on-ramp volume (vehicles/hour).

Although this methodology is not specifically for the analysis of auxiliary lanes and on-ramps, it would be applicable. In the case of ramp metering, the meter rates would lower V_R. The Redbook provides some sample capacity and free-flow rates for ramps.

4.0   RECENT RESEARCH AND FINDINGS

The next few sections provide an overview of recent research and findings related to traffic operations. Much of the research concerns the impact of weaving sections on capacities, speeds, volumes, level of service, and accident rates. While most directly applicable to the analysis of auxiliary lanes, the weaving research is relevant for most of the operational improvements considered for inclusion in the Cal-B/C update. The review includes a description of the development of the Leisch and Level D weaving analysis methods that are included in the Highway Design Manual.

A limited amount of information is available on HOV connectors and drop ramps, since these treatments are relatively new and are more common in California than in other states. The widening of on-ramps and off-ramps to accommodate ramp metering and demand has generally not been the subject of research and left as a standard design consideration.

The research and findings are presented in the following sections:

- Early Research on Weaving Sections
- Current Research on Weaving Sections
- Safety Issues Associated with Weaving
- Freeway and HOV Connectors
- HOV Drop Ramps
- On-Ramp and Off-Ramp Widening.

4.1   Early Research on Weaving Sections

Weaving sections have been the topic of research efforts as early as 1950, when the HCM presented a methodology for weaving design and analysis. The HCM 1950 methodology was based on field data collected at six weaving sites in the Washington D.C. and Arlington, Virginia areas in 1947. The HCM 1950 includes a chart that determines the operating characteristics of a weaving section given the length of the visible section before the weave, the speed on the freeway, and traffic density. Numerous methodologies have been developed since the HCM 1950, primarily using data collected from weave sections in the 1960s and 1970s.

Additional research (Normann, 1957; Hess, 1963; Leisch, 1958; Leisch, 1964) significantly expanded the analysis of weaving sections in the HCM 1965 (as cited in Glad, Milton, Olsen, 2001). The new HCM presented two separate procedures for analyzing freeway weaving sections. The first is a nomograph technique (graph with numerical relationships connected by lines) developed by Hess (1963 as cited in Cassidy, Chan, Robinson, May, 1990). This method considers three factors: weaving section length, total weaving volume, and the operational quality within the weaving area. Since the lines in the nomograph define the relationships between the three variables, only two are needed to estimate the value of the third variable. The relationship between weaving volume and effective capacity allow the analyst also to approximate an average vehicle speed for the weaving section. The HCM 1965 include a method for estimating the appropriate number of lanes for the weaving section.

The second technique found in the HCM 1965 was developed by Moskowitz (who won the 1957 Highway Research Award for his 1956 work on California Freeway Capacities). This technique is more heavily design focused and estimates whether a particular weave section can accommodate given traffic flows. The second technique is applicable only for ramp-weave freeway sections (weaving areas formed by a one-lane on-ramp followed by a one-lane off-ramp such as those found around auxiliary lanes).

The technique applies only to ramp-weave freeway sections that are operating at near capacity. Since these operating conditions correspond to a Level of Service (LOS) D, the procedure has come to be known as the Level D procedure. This procedure is still recommended in the California Highway Design Manual and is included in the FREQ modeling program.

Unlike previous models in which operating conditions are based on average travel speeds, the Level D procedure predicts the distribution of vehicles at any location within the right-most portion of the weaving area to determine operational performance. The procedure identifies the maximum through volume and amount of lane changing above which free-flow operation does not occur. The Level D technique was the first to consider traffic flow behavior within the weaving section – an approach which became the focus of much later research (see Moskowitz and Newman, 1963).

Following publication of the HCM 1965, researchers developed several techniques to calibrate the evaluation of weaving performance. The Transportation Research Board sponsored National Cooperative Highway Research Project (NHCRP) 3-15, "Weaving Area Operations Study," from 1971 to 1973 to evaluate the 1965 weave methods and to develop a new procedure for design and operations of weave sections. The study relied on the 1963 Bureau of Public Roads (BPR) database and more recently collected data and experiments. A follow-on study was conducted under the FHWA research program in the late 1970s.

To address a perceived gap between theory and practice, Jack Leisch and Associates, developed an extension of the HCM 1965 procedure before the FHWA study was completed. The procedure was first reported in a 1979 Institute of Transportation Engineers (ITE) Journal article (Leisch, 1979), subsequently expanded and published as an FHWA users guide (Leisch, 1985), and later incorporated in software distributed by McTrans called FAZWEAVE.[25] Leisch conducted independent statistical analyses using information from the 1963 BPR database and supplementary data from NHCRP 3-15 to develop his method.

The Leisch method follows most of the HCM 1965 definitions, but incorporates additional geometric information about the weave section. The method uses a nomograph approach to establish an appropriate length and number of lanes for the weaving section given traffic volumes and desired level of service. Leisch adopted a convention that differs from NHCRP 3-15 to group weaving sections into two categories: one sided (ramp weaves, irrespective of the number of ramp lanes) and two-side (entering and existing traffic from opposite sides weave across the traffic flow). These categories are further divided into "lane-balanced" and "lane-imbalanced" sections. Exhibit V-13 shows an example of a Leisch nomograph for a two-sided weaving section, such as those near a freeway connector. The California Highway

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[25] *FAZWEAVE, Version 2.20 - The Microcomputer Version of Four Weaving Operational Analysis And Design Procedures.*

Design Manual includes a Leisch nomograph for a one-sided weaving section. Leisch assumes that the average running speed for weaving traffic is 5 MPH less than average through operating speeds.

Exhibit V-13
Leisch Nomograph for a Two-Sided Weave Section
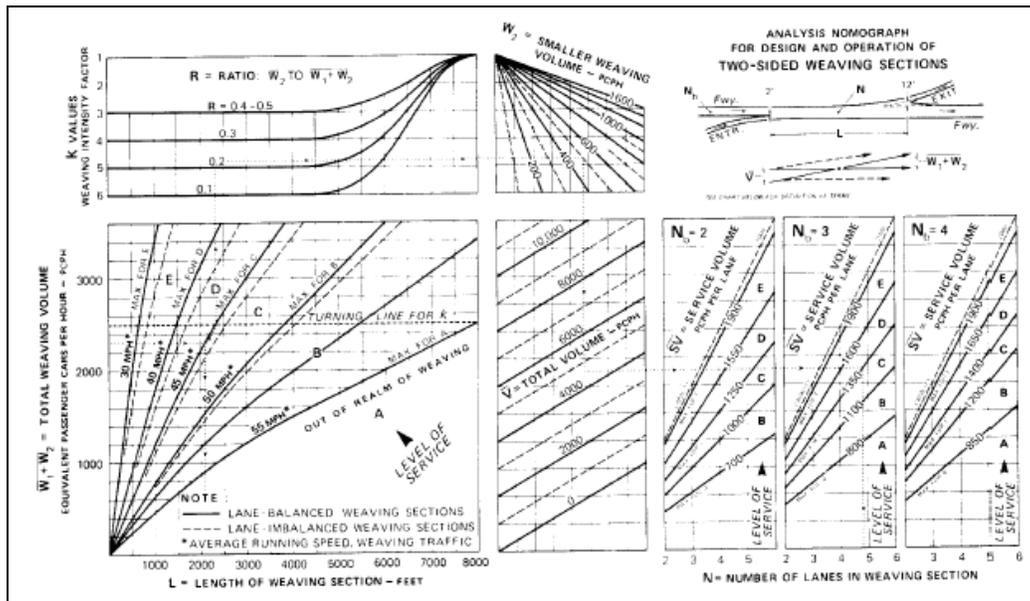
Source: Leisch, J., "A New Technique for Design and Analysis of Weaving Sections on Freeways," ITE Journal, Vol. 49, No. 3, March 1979.

Pignataro, McShane, Roess, Crowley, and Lee (1975) at the Polytechnic Institute of New York (PINY) were responsible for the method developed prior to Leisch under NCHRP 3-15. The procedures are quite complex and require iterative use of equations and/or nomographic techniques. The PINY group recognized that inaccuracies in the HCM 1965 could be traced to ambiguities in level of service standards, the k-factor equivalence expansion, and that lane configuration should play a role in design and analysis. As a result, the PINY method explicitly considers geometric considerations.

The NCHRP research found that lane configurations sometimes resulted in weaving vehicles using only a portion of the total roadway. The PINY group defined two weaving configurations: ramp weaving sections (consecutive on-ramp and off-ramp joined by an auxiliary lane) and major weave sections (three or more entryways form a major merge point or fork with two or more lanes). The PINY group concluded that ramp weaves take place primarily in shoulder and auxiliary lanes, while major merges can dominate the majority of the roadway.

In 1975, the PINY group authored NCHRP Report 159 with a new procedure based on the NCHRP 3-15 research that takes into account additional variables, including geometrics, traffic composition, main line volumes, and weaving volumes. The PINY method made several changes to the HCM 1965 procedure. The method can be used for

design purposes (to establish the appropriate number of lanes, weaving section length, given traffic volumes, and desired level of service) and for operational performance evaluation (as measured by average travel speeds for weaving and non-weaving traffic for given geometric characteristics and traffic flows). This later use corresponds to the applications needed for Cal-B/C update. Despite better accuracy and the inclusion of lane configurations, users found the complexity of the PINY method made it difficult to apply.

A modified procedure was developed and published with the nomographic technique developed by Leisch in an interim weaving procedure circular (TRB Circular 212, 1980). Although Circular 212 included both the PINY and the Leisch method, the two procedure frequently yielded substantially different results. As a result the FHWA sponsored research to compare the two methods and make recommendations for the HCM 1985. JHK and Associates conducted the research and concluded that neither procedure was adequate and developed a new procedure for estimating average travel speeds of weaving and non-weaving traffic (Reilly, Kell, Johnson, 1984).

The JHK procedure consists of two equations that were calibrated using regression techniques on fairly recently collected empirical data. The equations consider the length of the weaving section and the total number lanes, but in a departure from Leisch and PINY methods, do not consider the geometric configuration of the weave section.

The Highway Capacity and Quality of Service Committee of TRB sponsored more research to resolve the conflict between the PINY, Leisch, and JHK methods and develop a definitive procedure for the HCM 1985. Roess reported on that effort in Transportation Research Record 1112. Like the JHK model, the HCM 1985 weaving procedures estimate average speeds for weaving and non-weaving vehicles using equations calibrated using regression techniques. However, unlike the JHK models, the HCM 1985 explicitly considers the geometric configuration of the weave section. Complete descriptions were written for weave configurations based on the number of lane changes to complete a weaving maneuver. The HCM 1985 procedure also differentiates between constrained and unconstrained operations. Constrained operation occurs when weaving traffic streams are unable to segregate from non-weaving traffic. Under constrained operations, travel speeds are significantly lower for weaving traffic than they are for non-weaving traffic (Transportation Research Board, 1985).

Fazio and Rouphail (1986) examined the Leisch, JHK, and HCM 1985 methods and concluded that refinements were need to account for lane shifting occurring in anticipation of the merge. Fazio and Rouphail modified the JHK procedure to factor in geometric configuration and incorporate a variable reflecting the minimum number of lane-changing maneuvers a motorist must perform. They then tested their refined method against the other three methods at more than 50 sites nationally and found the Fazio method to be a better predictor. The researchers concluded that 1985 procedure

had limited applicability because of the constraints on weaving section capacity or length. They also determined lane shifting to be an important factor due to its influence on weaving and non-weaving speeds.

4.2   Current Research on Weaving Sections

Current research has focused on refining the weaving analysis methods contained in the Highway Capacity Manual. In the last ten years, many studies have begun to test the use of micro-simulation models for analysis of weaving sections. A consensus has begun to emerge that simulation models are more accurate a replicating field conditions and representing per-lane traffic flows and weaving movements, particularly in areas with complicated geometrics.

Since 1985, much of the research on weaving sections has occurred in California, particularly at the Institute of Transportation Studies at the University of California-Berkeley. Between 1987 and 1989, researchers at UCB conducted a two-year study on major freeway weaving sections, such as those near freeway interchanges.

Preliminary findings from the study are described in Skabardonis, Cassidy, May, and Cohen (1989). UCB researchers used the Integrated Traffic Simulation microscopic model (INTRAS) to study eight major freeway weaving sections in California (representing Caltrans Districts 4, 7, 8, and 11). The sites chosen included a range of configurations and design characteristics, such as weave section length and number of lanes, based on the weaving section definitions found in the HCM 1985 (Type A, B, and C). The model was calibrated using video recordings from each site. The researchers found that the average speeds predicted by INTRAS were close to the field data for all eight sites and that the patterns of simulation results were consisted. They then examined the HCM 1985 and Leisch analytical procedures. The researchers found that both methods underestimated speeds in the weaving sections and that the results across locations were inconsistent. The authors concluded that micro-simulation is a useful tool for analyzing weaving segments.

Cassidy, Skabardonis, and May (1989) describe subsequent efforts at UCB to test additional analytical methods for major freeway weaving analysis. The researchers compared the results from the HCM 1965, Leisch, PINY, JHK, HCM 1985, and Fazio methods using the same eight test sites as used in the earlier research. Cassidy et al. found significant discrepancies between the field-measured speeds and the speed predicted by the six models for weaving and non-weaving vehicles. Regional analysis and regression and classification trees were performed to identify basic relationships between weaving section design and traffic characteristics. The researchers found that the speeds predicted seemed to be insensitive to changes in geometric and traffic factors over the range of values in the data set and suggested that average travel speed is not a sound measure of effectiveness for freeway weaving areas.

As a result of this research, Cassidy and May (1991) observed that the operation of freeway weaving sections is influenced largely by what is occurring in individual lanes. The researchers proposed a new analytical procedure under the premise that operational performance is best modeled on a lane-by-lane basis. Rather than predict that average speed of vehicles in the weave section, the model predicts the distribution of vehicles within the rightmost lanes. Changes in vehicles over a given distance indicates lane changing activity. Both lane utilization and lane changing can be used to identify the capacity of the weaving area. The Cassidy and May approach expands on the Level D method developed by Moskowitz in 1963 for ramp-weave sections.

To test the method, Cassidy and May collect more than 30 hours of empirical data from nine major weaving sites in California. They found the flow parameter that influenced freeway-to-ramp flows most is the weaving flow rate. This suggests that lane-changing is a function of gap availability. The researchers tested the method with extensive simulation modeling using INTRAS. Weaving section capacity was found to be 2200 passenger cars per hour at any point in the weaving section and lane-changing capacity was found to range between 1100 and 1200 passenger cars per hour for any 250-foot segment within the weaving section.

The full two-year research effort is documented in Cassidy, Chan, Robinson, and May (1990). In the conclusion of the report, the authors offer design guidelines for establishing suitable weaving area geometrics. They note that the largest proportion of vehicles in weave areas remain on the freeway. Providing additional lanes upstream of the merge reduces the number of these vehicles in the lanes adjacent to the merge and diverge areas. A sufficient number of ramp lanes should be provided to insure that flows near ramps remain below 2200 passenger cars per hour per lane. Shorter segment lengths reduce operational quality and capacity.

Concurrent with the UCB research on major weaving sections, Caltrans researchers examined the appropriateness of capacity analysis procedures for the other type of freeway weaving sections, ramp-weaves. Fong and Rooney (1990) compared three procedures: the HCM 1965 Level of Service D procedure, the HCM 1985 procedure, and the Leisch method. They collected 17 datasets (eight peak period and nine non-peak period) for eleven weaving locations in Oakland, Los Angeles, and San Diego using video equipment. All eleven locations had diamond-type, one-lane ramps with auxiliary lanes connecting the on-ramps and off-ramps.

Fong and Rooney found that actual space mean speeds for weaving vehicles in these locations were typically about 50 to 60 mph. The calculated average speed for non-peak periods using the HCM 1985 procedure under-predicted actual speeds by 11 mph. The Leisch method under-predicted non-peak speeds by 9 mph. Fong and Rooney concluded that neither method was sufficiently accurate for California freeways. However, they determined that the level of service charts in the Leisch method were sufficiently accurate for the planning and design of typical weaving areas with one-lane ramps and auxiliary lanes, as the indicate capacities were within about 10 percent of

actual capacities. Rooney and Fong also found the Level D procedure to be a useful tool for planning and design. It predicted maximum rates of weaving vehicles in outer through lanes and auxiliary lanes in ramp-weave areas within about 10 percent of actual rates. The authors noted that peak-hour factors should usually be used for both the Leisch and Level of Service D procedures.

The procedure proposed by Cassidy and May (1991) for major weaving sections was incorporated by UCB researchers into a new simulation model called FREWAV. Ostrom, Leiman, and May (1993) used the model to compare alternative designs of major weaving sections.

Wang, Cassidy, Chan, and May (1993) continued the research conducted during the earlier two-year program. The researchers selected data from the previously collected video recordings for one Type B major weaving section (as defined in the Highway Capacity Manual). The used five hours of free-flow data and 30 minutes of high-flow data to calibrated an INTRAS model. The model was used to predict flows and lane changing rates within the weaving section. The model runs revealed two major factors affecting weaving capacity: 1) the highest point flows occur within 250 feet of the weaving section (which they defined as the critical region), and 3) merging and diverging movements create very high flows within a single lane segment of the weaving section.

To test the capacity of the region, the researchers allowed drivers to pre-segregate by coding advanced warning signs in the model and adjusting the distribution of vehicles in upstream lanes. Even when driver aggressiveness factors were adjusted, the researchers found that the weaving section could handle in the critical region a total flow (through traffic plus entering and exiting traffic) of no more than 5900 pcph. They also found that capacity was exceeded when per-lane traffic demand exceeded 2200 pcph. The highest proportion of lane changing activity was observed near the merge gore.

At the Texas Transportation Institute, Barnes (1993) also validated the use of microscopic simulation models for the analysis of weaving sections. Texas was beginning to build weaving sections on freeways with four or more lanes and needed guidance for constructing auxiliary lanes. Barnes began by examining the HCM 1985 methodology and found that it consistently underestimated operations on the weaving sections. Barnes examined five micro-simulation models: CORFLO, FREQ, FREWEAV, INTRAS, and FRESIM. CORFLO and FREQ were rejected for providing to course of measurement and FREWEAV was rejected because it models only Type B and C weaving sections. Barnes deemed INTRAS to be appropriate for the study, but selected FRESIM because it is an enhanced PC-version of INTRAS. He collected videotape and other empirical data for highway weaving sections and demonstrated that FRESIM could predict weaving operations fairly well. Using the output of the FRESIM model, Barnes produced for four-lane and five-lane freeways operational matrices that show

average speed for merge-diverge areas based on the average mainline flow rate, the ramp flow rate, and the ramp spacing.

Kwon (1999) examined flow patterns and the resulting capacity reduction for ramp-weave sections in the Minneapolis-Saint Paul (Twin Cities) area. Kwon identified the primary weaving areas in the Twin Cities and classified the sites on the basis of the length and geometric configuration of the weaving areas. Loop detector data were collected for six of the sites and two-days of video data for one site. Kwon observed that exiting vehicles merge with entering vehicles on the auxiliary lane, which he called merge-split behavior. The mixed flow shares a portion of the auxiliary lane, the distance of which depends on the weaving flow. Kwon concluded that the maximum weaving volume (sum of entering and exiting vehicles) in a short ramp-weave section is limited by the maximum through volume (capacity) of the auxiliary lane, not the length of the auxiliary lane. The empirical data confirmed that the weaving section volume matches that of the leftmost lane upstream of the weaving section.

Kwon also found that the speed of exiting vehicles is primarily a function of the length of the auxiliary lane and the exit ramp capacity and that the speed of these vehicles did not vary with volume. As a result of the merge-split behavior, the speed of merging vehicle was similar to that of the exiting vehicles. Both flows were affected by downstream conditions.

The merge-split behavior also affected the flow of the mainline freeway. The rightmost lane had the highest occupancy and lowest flow of any lane on the freeway. This also causes friction on the middle lane, which has substantially lower flow than left-hand lanes. Kwon concluded that the greatest reduction in mainline capacity occurs immediately upstream of the weave section. On the basis of these observations, Kwon developed an estimation model for weaving sections and found a four to five percent variation between predicted and observed maximum weaving volumes.

Glad, Milton, and Olson (2001) at the Washington State Department of Transportation (WSDOT) conducted a two-year study from 1999 to 2001 of design alternatives for a weave section on I-5 in Olympia. The road section had been reconstructed in the early 1980s and now experienced operational problems. The WSDOT researchers began by reviewing recent literature on the analysis of weaving sections. They found support in the literature for micro-simulation and decided to use the ITRAF micro-simulation model (which is a successor to FRESIM and INTRAS) to test alternatives. The WSDOT Design Manual specifies using the 1997 HCM and Leisch techniques, so these methods were compared to the micro-simulation results for weaving analysis.

The researchers simulated a ten-mile corridor that included 39 ramps. Traffic data were gathered for a one-week period during January 1999 and the highest peak-hour counts were chosen for analysis. The researchers tested level of service impacts for four design alternatives and the existing configuration. The simulation model consistently produced lower speeds and levels of service than the two methods specified in the

WSDOT Design Manual (1997 HCM and Leisch). Although the findings could not be validated statistically, the authors concluded that the simulation model appeared to capture the geometrics better. They also decided that the HCM produces questionable results, particularly when complicated geometrics are involved. They suggested that Washington state continue to look at simulation modeling, but that the approach looked promising. The only drawback to modeling is that it is time consuming and data intensive.

As part of a Major Investment Study (MIS) in Dallas, Texas, Batenhorst and Gerken (2000) analyzed various auxiliary ramp designs at 20 sites using the 1997 HCM software, the CORSIM microscopic simulation model, and the Synchro/Simtraffic model. AASHTO lane balance principles suggest that a one-lane exit ramp can be used for auxiliary lane of less than 1500 feet in length. Longer auxiliary lanes must be terminated in a two-lane ramp or a one-lane ramp with a downstream taper. The simulations produced fairly consistent results regardless of model that suggested one-lane exit ramps are the best design for any length auxiliary lane.

Skabardonis (2002) applied CORSIM to eight weaving sites in California to develop better guidance for the use of simulation models. Skabardonis found that the default settings in CORSIM under predicts speeds in the weaving sections by 19 percent on average. After adjusting several parameters, he concluded that three significantly affected the simulation results: 1) car-following sensitivity, 2) lane-changing aggressiveness, and 3) percentage of through vehicles yielding to merging traffic. After adjusting these factors, Skabardonis was able to replicate observed speed within five miles per hour in the model.

Concurrent with the research on micro-simulation models, the NCHRP has continued to update the HCM procedures. Roess, McShane, and Prassas adjusted the 1985 procedures to account for the under-estimation of average operating speeds that had been observed in empirical studies. The new procedures were adopted for the 1997 HCM (as cited in Glad, Milton, Olson 2001).

For the 2000 Highway Capacity Manual, NCHRP sponsored another study of weaving sections. Project 3-55(5) relied on simulation models and developed a new method that differed substantially from the previous HCM definitions for capacity. This method was rejected. The Highway Capacity and Quality of Service Committee sponsored a second project to attempt to incorporate the capacity concepts developed under Project 3-55(5) into the 1997 HCM procedures. Roess and Ulerio (2000) relied on 21 hours of data collected from 18 sites in 1983. They developed adjustments for the speeds of weaving and non-weaving vehicles, the weaving intensity factors, and the capacity of the weaving section. The recommendations were adopted in the HCM 2000. The new procedure continues to suggest that the length of the weaving section influences its capacity, particularly for Type A sections.

NCHRP has tentatively selected Project 3-75 (Procedures for Analysis of Freeway Weaving Areas and Ramp Junctions) for FY 2004. The objective of this research is to develop new methodologies for operational analysis using a database of ramp-freeway junctions collected under project 3-37 in the early 1990s and the collection of new field data for weave areas. Previous procedures had been developed using in compatible and out-dated databases. The methodologies developed in the new research should estimate the capacity of weaving areas and ramp junctions as well as determine appropriate performance measures.

4.3   Safety Issues Associated with Weaving

A large body of safety research has suggested that accident rates increase as the number of passing maneuvers and traffic flow conflicts increase. However, very few researchers have examined the impact of weaving on safety.

One of the best known studies is the Interstate System Accident Research (ISAR) study undertaken by FHWA in the late 1960s. Crillo (1970) examined accident data collected during the study from 700 weaving sections, acceleration lanes, and decelerations lanes located in 20 states. After grouping data by average daily traffic (ADT), Crillo concluded that longer weaving sections lowered accident rates for weaving sections with ADT greater than 10,000, but had no effect for sections with lower traffic volumes. As the amount of merging or diverging traffic increased, the accident rate increased regardless of the length of the weaving section. However, shorter weaving sections also increased the accident rate regardless of the percentage of merging or diverging traffic (but particularly above 6 percent merging). The effects were much larger for acceleration lanes, which also experienced higher accident rates.

As part of a six-volume FHWA compendium called *Safety Effectiveness of Highway Design Features*, Twomey, Heckman, Hayward, and Zuk (1993) reviewed research on accident rates related to interchange features. The studies reviewed found that providing auxiliary lanes or at least 800 feet between entrance and exit ramps increases safety. Longer weaving lengths also provide greater safety. Accident rates are related to merging and through traffic volumes. Also, accident rates decline as interchange spacing increases in urban areas, particularly with interchanges more than one mile apart. Rehabilitation to interchanges also appeared to improve safety. Modifications to full diamond interchanges (including lengthening of acceleration or deceleration lanes, adding ramp lanes, and optimizing existing or installing new ramp signals) led to safety improvements of 20 to 33 percent. Modifications to partial clover-leaf interchanges (including the addition of collector-distributor roads, lengthening of weave areas, and lengthening of acceleration or deceleration lanes) led to safety improvements of about 40 percent. On average, ramp improvements led to a reduction in accident rates of 16.3 percent.

Fazio, Holden, and Rouphail (1993) hypothesized that analyzing conflicts could be a good indicator of safety for weaving sections. The authors used the INTRAS simulation

program to model ten ramp weaving sections. They found that the program could simulate two types of traffic conflicts that could potentially lead to crashes: following conflicts (precursors to rear-end accidents) and lane-changing conflicts (precursors to sideswipe and angle accidents). The authors concluded that weaving sections shorter than 500 feet experience higher conflict rates but have lower crash rates than other weaving sections.

Under contract to the Turner-Fairbanks Highway Research Center of FHWA, Bauer and Harwood (1997) developed a statistical model to define the relationship between accident rates and geometric design and traffic volumes for interchange ramps and speed-change lanes. The researchers developed a database for the model using information for Washington State from the FHWA Highway Safety Information System. The researchers examined the California TASAS database, but was rejected as a source since it does not include information on the geometrics of individual ramps. The most statistically significant variables found to affect accident rates were: ramp average annual daily traffic (AADT), mainline freeway AADT, rural/urban area type, on-ramp versus off-ramp, ramp configuration (diamond/loop/outer connection/direct or semi-direct connection), ramp length, and length of the speed-change lane. Ramp AADT was the strongest predictor of accident frequency. While statistically significant, the other variables had much less predictive ability.

As part of their two-year study of a weaving section on I-5 in Olympia, Glad, Milton, and Olson (2001) analyzed the safety impacts of the current configuration. They gathered accident statistics for a two-mile section during a three-year period (1994 to 1996) and grouped the data by location at 0.1-mile increments. The researchers found that during the peak period, the predominant proportion of accidents were rear-end accidents due to queuing from the weaving section. Most of the accidents were property damage only (PDO) because speeds were relatively low. Much higher accident rates (roughly three times those of other locations in the corridor) occurred at the start of the merge. During the off-peak, high speeds led to side-swipe accidents in addition to the rear-end collisions. The higher speeds also led to a small increase in fixed-object collisions as drivers tried to avoid slow or stopped vehicles. Accident severity was greater and most of the accidents occurred in the right-lane of the freeway.

Golob, Recker, and Alvarez (2002) used 1998 TASAS data to examine accidents on 55 weaving sections on five freeways in Orange County. The weaving sections cover 22.9 or 10 percent of the total route lengths in Orange County. The researchers found that of the 7,400 mainline crashes, 829 (11 percent) occurred within one of the 55 weaving areas. Crashes in weaving sections were more likely to be sideswipes than on other sections of the freeway. As shown in Exhibit V-14, accidents in the weaving sections were more likely to occur in interior lanes. The researchers suggested that the difference may be due to differences in the number of lanes.

Exhibit V-14
Location of Collisions in Weaving Sections
Compared to Other Freeway Sections
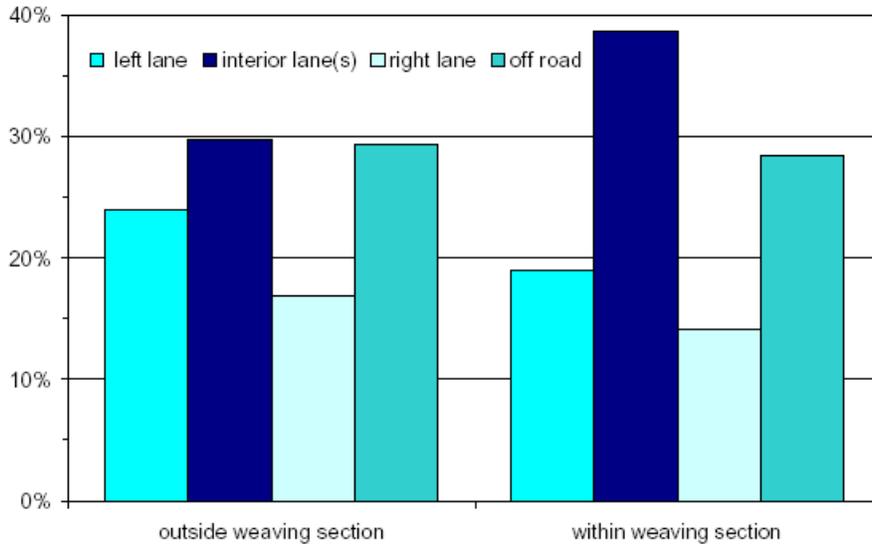
Source: Golob, T.F., Recker, W., Alvarez, V.M., Safety Aspects of Freeway Weaving Sections,
Institute of Transportation Studies, University of California, Irvine, UCI-ITS-WP-02-3,
July 2002.

They found no other statistically significant differences between crashes located within weaving sections and those located elsewhere on the same freeways in terms of: severity (measured in terms of injuries versus property damage only), number of vehicles involved, whether or not a truck was involved in the crash, weather conditions, or temporal distributions (by time of day, day of the week, and daytime versus nighttime).

The researchers developed a multivariate statistical model to determine how weaving section crashes differ from crashes on mainline freeway sections and among weaving section types, using the HCM nomenclature. They found that crashes within Type A weaving sections (merging or diverging vehicle must execute one lane change) are more likely to be located in an interior lane, be less severe, and occur off-peak or at night. Crashes within Type B weaving sections (either merging or diverging can be done without changing lanes) are more likely to involve lane changes, are less likely to be located in an interior lane, and are more likely to involve injuries. Crashes within Type C weaving sections (one maneuver requires at least two lane changes) are more likely to occur in the left lane and during weekday peak periods, and are less likely to occur on wet road surfaces.

The influence of weaving can also be inferred from accident statistics for HOV facilities. As shown in Exhibit V-15, accident rates on barrier-separated HOV facilities are lower than those found on buffer-separated and non-separated facilities. Barrier-separated facilities have a physical restraint between the HOV lanes and the adjacent mixed-flow

(or general purpose) lanes. Buffer-separate lanes provide no physical barrier, but rather extra space between lanes. In non-separated facilities, the HOV lane is simply the leftmost lane on the facility with no distinctions other than signage. Most HOV facilities in California are buffer-separated and the California standard for the buffer width has become the de-facto standard nationally.

Although the differences in accident rates may be due to other factors (traffic volume, weather, driving conditions, etc.), it is reasonable to assume that barrier-separated facilities reduce accident rates on HOV lanes by reducing the number of opportunities for weaving. This is further illustrated by the difference in accident rates between HOV lanes and the adjacent mixed-flow lanes. As shown in Exhibit V-15, HOV accident rates are lower than adjacent mixed-flow lane rates, when the facilities are separated by barriers. HOV facilities often consist of a single lane (although there are several instances of facilities with more than one lane in Southern California), while the adjacent mixed-flow facilities consist of several lanes. The higher accident rates on mixed-flow facilities can be attributed to greater opportunities for merging.

When HOV and mixed-lane facilities are not barrier-separated, the HOV lanes have higher accident rates than do the mixed-flow lanes. In these cases, the HOV lanes are potentially subject to as much merging as the mixed-flow lanes. In addition, accident rates are affected by the greater differential between the HOV and mixed-flow lanes than among the mixed-flow lanes.

Exhibit V-15
Comparison of HOV and Adjacent Facility Accident Rates

	f Accidents Per Million Vehicle Miles	
		Adjacent Mixed-Flow Lanes
BARRIER-SEPARATED FACILITIES		
		2.4
		2.4
		1.1
		N/A
BUFFER-SEPARATED AND NON-SEPARATED FACILITIES		
		2.1
		1.3
		1.4
		2.0
		3.6

Source: Charles A. Fuhs, High-Occupancy Vehicle Facilities: A Planning, Design, and Operation Manual, Parsons, Brinckerhoff, Quade, and Douglas, 1990 as cited in Cambridge Systematics, Inc., et al., Characteristics of Urban Transportation Systems, 1992.

4.4   Freeway and HOV Connectors

The research literature on freeway connectors has focused on weaving and safety issues occurring in major weaving sections. Although limited, this research is summarized in Sections 5.1 and 5.2.

No research was found related to HOV connectors, but the analysis issues are likely to be similar to those for HOV lanes and freeway connectors combined. Professor Adolf May of UC Berkeley has recently begun research on the impacts of HOV connectors for the Southern California Association of Governments (SCAG) as part of a regional HOV System Performance Study in the Los Angeles. Professor May anticipates developing a method to conduct benefit-cost assessments of HOV freeway-to-freeway interchange connectors. The work was anticipated to be completed at the end of 2004 and was not available in time for the Cal-B/C update.

4.5   HOV Drop Ramps

Most of the recent research on highway ramps has focused on design speed and truck performance rather than ramps appropriate for HOV facilities or ramp metering.

Over the last several years, the State of Texas has considered implementing a managed lane concept for several freeway projects in Texas cities. Texas DOT (TxDOT) defines managed lanes as encompassing several facility types, including HOV lanes, high occupancy toll (HOT) lanes, single occupancy vehicle (SOV) express lanes, special use lanes, and truck lanes. The Texas Transportation Institute (TTI) has conducted a number of research activities over the last three years to support state decision making regarding managed lanes. The research activities have examined marketing, planning, and design issues related to managed lanes.

In a study sponsored jointly by the FHWA and TxDOT entitled "Entry-Exit and Intersection Design Criteria for Barrier-Separated HOV Facilities," TTI examined the experience of several states in the development of managed lanes. The study examined critical design elements including geometric design criteria, the link between operations, design and enforcement, as well as ingress and egress treatments (Eisele, Parham and Cothron, 2001).

Research continued under another study sponsored by TxDOT entitled "Operating Freeways with Managed Lanes." In 2002, TTI conducted an on-line literature search of state DOT design manuals to determine the current state of the practice in designing ramps for managed lane facilities (including HOV lanes). Of the 23 states that had all or part of their design manuals available online, only 12 had material available regarding ramp design. The design manuals contained limited guidance for managed lane facilities (Fitzpatrick, Brewer and Venglar, 2003).

As part of the study, Venglar, Fenno, Goel, and Schrader (2002) evaluated the effect of different ramp spacings, volume levels and weaving percentages using the VISSUM simulation tool for a 13-mile stretch of I-10 in Houston, Texas. Baseline simulation results were calibrated to vehicle classifications conducted by TTI in December 1999 and traffic weaving behavior found in the Highway Capacity Manual. TTI adopted a simulation approach for modeling HOV drop ramps because the project advisory committee determined that HOV drop ramps and connectors are not adequately covered using existing analytic tools and design standards.

Researchers were able to vary the amount of traffic weaving to enter the HOV lanes, the freeway volume, and the entrance/exit ramp spacing. They found that when the percentage of weaving traffic is under 30 percent, average freeways speeds were not substantially reduced, regardless of the ramp spacing. Once the percentage of weaving traffic reached 30 percent, the weaving maneuvers substantially impacted freeway performance. The most significant impacts occurred when freeway volumes were 1750 vphpl or greater. With these volumes, ramp spacing of 2500 feet or less resulted in average freeway speeds below 40 mph on the mainline freeway, but free-flow conditions on the HOV lanes. Larger ramp spacing improved mainline freeway speeds, but reduced HOV lane speeds to about 40 mph.

However, as Exhibit V-16 shows, the researchers found that even a small percentage of weaving traffic could lead to notable reductions in freeway speeds. The effect on weaving speeds is even greater. Average entrance weave speeds below 45 mph occur when approximately 300 vehicle per hour are attempting to weave.

Exhibit V-16
Minimum and Average Freeway Speeds for Different Weaving Levels

		Average Speed (mph)
		44
		37
		21
		20

Adapted from: Fitzpatrick, K., Brewer, M.A., and Vengler, S.P., Managed Lane Ramp and Roadway Design Issues, Texas Transportation Institute, Report Number 4160-10, January 2003.

The researchers recommended that a drop ramp or direct connector should be considered whenever HOV lane usage is anticipated to exceed 400 vehicles per hour. A more conservative threshold was established at 275 vehicles per hour (the lowest flow rate at which speeds less than 45 mph were simulated).

4.6 On-Ramp and Off-Ramp Widening

As part of a 2000 study for TxDOT, researchers at TTI conducted a study of designing freeway on-ramps to accommodate ramp metering queues. Texas has begun to introduce ramp metering in some urban areas. However, many existing freeway ramps in Texas were not designed with ramp metering in mind. TxDOT does not have guidelines for designing freeway entrance ramps with explicit consideration of ramp metering.

TTI examine ramp metering practices in Texas and other states to identify key factors. On the basis of these factors, researchers developed a spreadsheet-based analytical tool to study design variables and verified results using simulations. This work led to the development of ramp metering design criteria for Texas.

TTI researchers found that ramp metering is typically installed to achieve any combination of three objectives:

1) Control the number of vehicles entering the freeway to keep freeway demand below operating capacity

2) Encourage traffic diversion through controlled delay to reduce freeway demand

3)   Breakup vehicle platoons to facilitate vehicle merging (Chaudhary and Messer, 2001).

Texas handles excess vehicle queuing on ramps in the same manner as California. Queues are prevented from spilling into upstream traffic signals through the use of queue detectors. When the queue detector (a sensor at the ramp entrance) determines that queues are becoming excessively long, metering operations are sped up or turned off until the queue is cleared. Texas researchers found that excess demand leads to ramp metering functioning (or available) less than 100 percent of the time. Exhibit V-17 shows the operational efficiency of ramp metering as a result of queue flushing.

Researchers noted that ramp must provide sufficient storage to accommodate short-term demand. Even when long-term demand (five minutes or more) is less than the meter capacity, upstream signals may cause vehicle platooning that exceeds demand in the short term. If sufficient vehicle storage is not available, ramp meters remain in flush mode and the ramp metering strategy loses efficiency and produces lower than expected benefits as illustrated in Exhibit V-17.

Exhibit V-17
Impact of Ramp Demand on the Quality of Ramp Metering
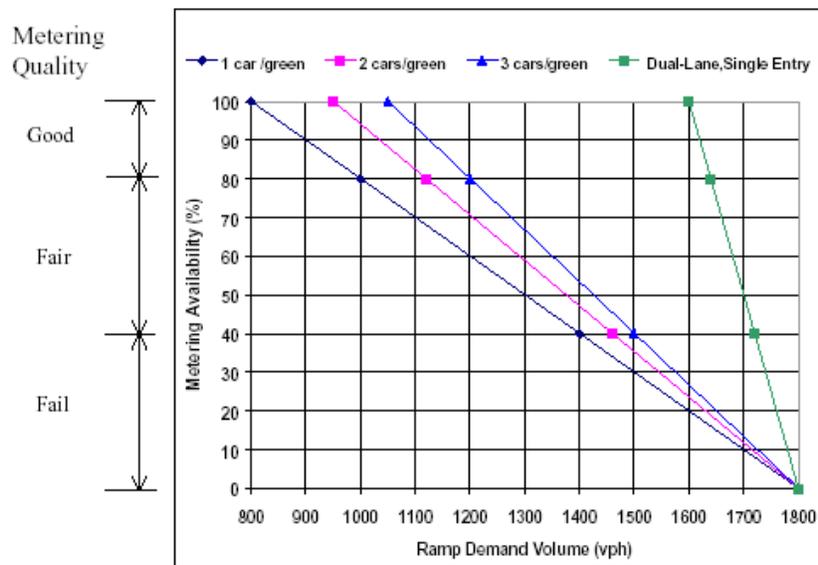
Source: Chaudhary and Messer, 2000.

A well-designed on-ramp should provide sufficient storage space and a metering capacity that exceeds traffic demand. The TTI researchers provided recommended distances from the upstream intersection to the ramp meter (see Exhibit V-18) to accommodate safe vehicle stopping at the ramp and queuing.

Exhibit V-18
Texas Recommended Distance from Intersection to Meter
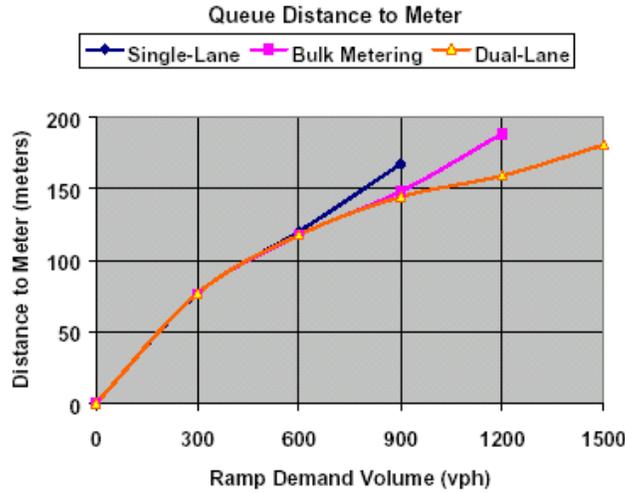
Source: Chaudhary and Messer, 2000.

The ramp should also have sufficient distance after the ramp meter to allow vehicles to achieve safe merging speeds. The TTI researchers provided recommendations for this additional distance as shown in Exhibit V-19.

Exhibit V-19
Texas Recommended Acceleration Length to Merge Point
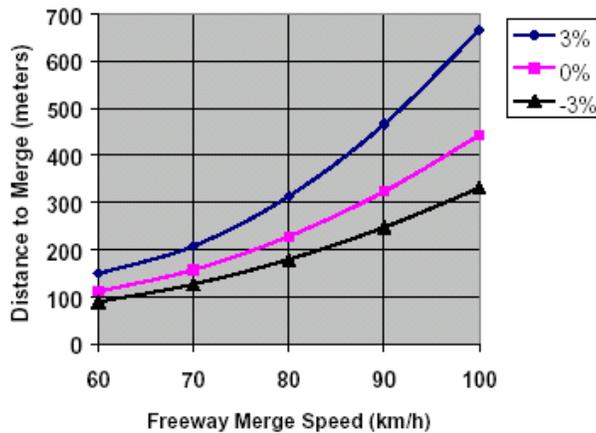
Source: Chaudhary and Messer, 2000.

A second TTI study examined the delays to frontage roads vehicles due to vehicles on freeway on-ramps. The predominant freeway design practice in Texas is to provide frontage roads along freeways. Exit ramps connect merge with the frontage roads rather than connecting directly with intersecting surface streets. A 1979 Texas law requires frontage road traffic to yield to entry and exit ramp traffic. This configuration eliminates or reduces significantly delay on the mainline freeway due to queued exiting vehicles, but it can delays to frontage road traffic.

Gattis, Messer, and Stover (1988) collected information from four different exit ramp configurations commonly found in medium-sized Texas cities. They modeled the traffic as a Poisson process and estimated delay to frontage vehicles as a function of ramp volume, frontage road volume, and gap acceptance using queuing theory. However, the results of this study are not applicable to California freeways due to the differences in configuration.

5.0 CAL-B/C METHODOLOGY

The next few subsections describe the Cal-B/C methodology in terms of the specific algorithms, necessary data (e.g., lookup tables, factors, etc.), and their sources for each of the operational improvement types added in the most recent update.

Each subsection is devoted to a specific type of project and provides the following discussion:

- Impacts Analyzed – identifies the specific impacts analyzed by the new approach.

- User Inputs – describes any new user-provided data required to complete the analysis that is not already included in the base version of Cal-B/C.

- Impact Calculation – describes the approach for estimating the incremental change on various impact categories due to the implementation of the project. This section also describes the process for assigning a dollar benefit value to the estimated impacts if it differs from the base Cal-B/C approach.

- Major Assumptions – identifies significant assumptions made or potential limitations of the methodology for the Cal-B/C update.

5.1 Auxiliary Lanes

The Cal-B/C update analyzes auxiliary lanes as simple weaving sections. The new AASHTO Redbook recommends using the procedures found in the HCM 2000. Cal-B/C uses the formulas found in the HCM 2000 to estimate speeds before and after the project using the AASHTO method. The research by Fong and Rooney (1990) documented that the HCM formulas generally under-predict highway speeds by 10 percent. As agreed by the project Advisory Committee, the Cal-B/C update includes a correction factor of 10 percent applied to the HCM formulas to account for under-predictions of highway speeds.

Impacts Analyzed

Cal-B/C analyzes changes in:

- Travel time
- Vehicle operating costs
- Emissions.

Although auxiliary lane projects are often justified in terms of potential safety benefits, the research did not find empirical support for safety benefits associated with auxiliary lanes. The "Model Inputs" page of Cal-B/C allows users to enter a percent reduction in accident rates if future research or project-specific data support these benefits.

User Inputs

Users are asked to enter the following information:

- *Ramp design speed* – This should be the design speed in mph for the on-ramp that the auxiliary lane extends. The HCM formulas use the ramp design speed to estimate the speeds of traffic involved in weaving.

- *Percent of highway traffic involved in weaving* – This is the volume of traffic on the mainline highway that is involved in weaving (in vehicles per hour). Cal-B/C provides a default value for this percentage by assuming that only traffic in the two right-most lanes are involved in weaving and that traffic is evenly dispersed across all lanes. This is the same assumption as is found in the latest AASHTO Redbook. Cal-B/C also assumes that users enter information for one direction only, so the percentage is calculated as 2/number of lanes.

- *Hourly on-ramp volume* - Users are asked to estimate the volume at the auxiliary lane on-ramp in vehicles per hour (vph) during a typical peak and non-peak hour. The model provides a default value for peak periods of 1350 vph, which represents that average capacity of a freeway ramp according to Table 3-4 of the AASHTO Redbook (which lists capacities between 1300 vph for ramps in the urban core and 1400 vph in rural, suburban, and other urban areas). This compares with the California Highway Design Manual recommendation of a 300 meters auxiliary lane, whenever ramp volumes exceed 1500 vph. The model estimates non-peak period hourly ramp volumes using the peak period input, the length of the peak period input, and the percent ADT occurring during a typical peak hour default in the Parameters page. This results in a default of 556 vph if the 1350 vph default is not changed. Users may also change the non-peak ramp volume.

- *Length of the project* – This is entered as the project length in miles. The before length should equal the on-ramp without the auxiliary lane. The after length should equal the on-ramp plus the auxiliary lane. Since most acceleration lanes are measured in feet or meters, users must convert the measurement to miles before entering the data into Cal-B/C.

- *Length of the area affected by the auxiliary lane* – Users should enter the distance over which speeds on the highway are improved by the auxiliary lane. The model includes a default of 1500 feet, which is the standard affected area found in the HCM for auxiliary lanes.

Impact Calculation

- **Travel time** benefits are calculated using the AASHTO-recommended (HCM) method for analyzing simple ramp weaves. A correction factor of 10 percent is applied to account for under-predictions of speeds, using the following formulas:

$$S_R = S_{FF} - (S_{FF} - 42)M_S \qquad and$$

$$M_S = 0.321 + 0.0039\,e^{(V_{R12}/1000)} - 0.002(L_A S_{FR}/1000)$$

   - S_R = space mean speed of vehicles within ramp influence area (mph)
   - S_{FF} = free-flow speed of freeway approaching merge area (mph)
   - M_S = intermediate speed determination variable for merge area
   - V_{R12} = sum of flow rates for ramp and vehicles entering ramp influence area in right-most two lanes (vehicles/hour).
   - L_A = the length of the acceleration lane (feet)
   - S_{FR} = free-flow speed of ramp (mph).

- According to the California Commercial Driver Handbook (2001), trucks and other heavy vehicles must remain in the two right-most lanes of the highway. Since these are the lanes influenced by weaving according to the HCM, Cal-B/C assumes that all trucks on the highway are influenced by weaving. The remaining percentage of traffic that is influenced by weaving on the highway is assigned to a new category of vehicles called "weaving vehicles." The volume of traffic on the on-ramp is also added to this category, since these vehicles are involved in the weave. Note that the sum of the truck volumes and weaving volumes equal V_{R12} in the HCM speed formulas.

- The model calculates both before and after speeds for trucks and other weaving vehicles using the HCM formulas. Speeds are calculated using the before and after segment lengths (i.e., on-ramp distance versus the on-ramp plus auxiliary lane distance). Travel time benefits are estimated over the affected area. Users can change the speeds estimated by the model in the "Model Inputs" sheet if project-specific data are available from simulation models.

- Changes in **vehicle operating costs** and **emissions** are estimated as a function in speed improvements that result from auxiliary lanes facilitating weaving. Benefits are estimated over the affected area. Operating cost and emission rates are not adjusted.

- Cal-B/C allows **safety** rates to be adjusted by a percentage entered by the user on the "Model Inputs" page. This adjustment is set to a default of 0 percent.

Major Assumptions

- The Cal-B/C methodology ignores potential induced demand from parallel arterials.

- The methodology also does not consider the impacts of lane configuration, the spacing of intersections, and other factors that may influence the effectiveness of auxiliary lanes.

5.2   Off-Ramp Widening

Off-ramp widening projects benefit highway users by reducing queues and associated weaving at the junction of highways with off-ramps. Cal-B/C models these projects similar to auxiliary lanes for travel time, vehicle operating cost, and emissions reductions. It is assumed that traffic in the right-most lane must merge into other highway lanes to avoid the queue that extends from the off-ramp onto the mainline freeway. The right-most lane operates like an on-ramp and the next two lanes are influence by merging as would occur for the two right-most lanes with an auxiliary lane. Off-ramp widening projects also provide safety benefits due to reduced end of queue collisions. Except for safety, the user benefits of off-ramp widening and auxiliary lanes are modeled similarly.

Impacts Analyzed

The impacts analyzed by Cal-B/C include changes in:

- Travel time
- Vehicle operating costs

- Emissions
- Safety.

User Inputs

The user inputs for off-ramp projects are fairly similar to those for auxiliary lanes:

- *Ramp design speed* – The HCM formulas use the ramp design speed to estimate the speeds of traffic involved in weaving. For an off-ramp widening project, this is the approaching speed for traffic in the right-most highway lane. Cal-B/C provides a default value of 35 mph, which is a fairly typical ramp design speed in California. Unless the user has a better estimate of the approach speed for traffic in the rightmost lane (value should be less than the highway free-flow speed due to weaving), this default value should remain unchanged.

- *Percent of highway traffic involved in weaving* – This is the volume of traffic on the mainline highway that is involved in weaving (in vehicles per hour). Cal-B/C provides a default value for this percentage by assuming that traffic in the three right-most lanes (the right-most lane plus the two neighboring lanes) are involved in weaving and that traffic is evenly dispersed across all lanes. Cal-B/C also assumes that users enter information for one direction only, so the percentage is calculated as 3/number of lanes. Note that the on-ramp volume is not needed for off-ramp widening projects as it is for auxiliary lane projects, since the right-most lane is assumed to function like an on-ramp.

- *Weaving Distance* – This is the distance in miles over which traffic in the right-most lane must merge into the two next lanes and avoid the end of the off-ramp queue. This distance is influenced by many factors, such as curvature, sight distance, weather, driver aggressiveness, etc. However, the typical weaving distance is probably similar to the distance provided for on-ramp merges. The California Highway Design Manual provides a distance of 1083 feet for on-ramps. The Cal-B/C model uses this as the weaving distance. Users cannot change this value.

- *Length of the area affected by weaving* – This is the distance over which traffic in neighboring lanes is affected by merging from the right-most lane. As for auxiliary lanes, the model provides a default impact area of 1500 feet on the highway.

Impact Calculation

Cal-B/C estimates the impacts of off-ramp widening as similar to those for auxiliary lanes:

- **Travel time** benefits are calculated using the AASHTO-recommended (HCM) method for analyzing simple ramp weaves. A correction factor of 10 percent is applied to account for under-predictions of speeds, using the following formulas:

$$S_R = S_{FF} - \left(S_{FF} - 42\right)M_S \qquad and$$

$$M_S = 0.321 + 0.0039\,e^{\left(V_{R12}/1000\right)} - 0.002(L_A S_{FR}/1000)$$

  – S_R = space mean speed of vehicles within ramp influence area (mph)
  – S_{FF} = free-flow speed of freeway approaching merge area (mph)
  – M_S = intermediate speed determination variable for merge area
  – V_{R12} = sum of flow rates for vehicles entering ramp influence area in three right-most lanes (vehicles/hour).
  – L_A = the length of the weaving section (feet)
  – S_{FR} = free-flow speed of ramp (mph).

- Cal-B/C assumes that all trucks on the highway are influenced by weaving. The remaining percentage of traffic that is influenced by weaving on the highway is assigned to a new category of vehicles called "weaving vehicles. The sum of the truck volumes and weaving volumes equal V_{R12} in the HCM speed formulas.

- The model calculates speeds without the project for trucks and other weaving vehicles using the HCM formulas and a 1083 feet for the "length of the acceleration lane." Speeds for other vehicles are calculated using the standard Cal-B/C method (BPR curve). Speeds with the project for all vehicles are calculated using the BPR method. Travel time benefits are estimated over the affected area (default = 1500 feet). Users can change the speeds estimated by the model in the "Model Inputs" sheet if project-specific data are available from simulation models.

- Changes in **vehicle operating costs** and **emissions** are estimated as a function in speed improvements that result from auxiliary lanes facilitating weaving. Benefits are estimated over the affected area. Operating cost and emission rates are not adjusted.

- For **safety** benefits, accident rates are assumed to be cut in half using the factors found in the research by Sullivan. This assumption is included in the parameters section of the model and can be adjusted by users.

Major Assumptions

- Before the widening project, queuing at the off-ramp is assumed to spill onto the highway causing vehicles in the right-most lane to merge.

- The weaving is assumed to occur over a distance of 1083 feet, which is the typical distance for an on-ramp.

- Other assumptions are similar to those for auxiliary lanes.

5.3   Freeway Connectors

Highway freeway connector projects can include the construction of new connectors, geometric corrections on existing connectors, or adjustments that improve major weaving sections. Caltrans does not expect many new connectors to be constructed in the foreseeable future, so Cal-B/C provides a methodology for estimating the benefit of the other two types of freeway connector projects.

For freeway connector projects that improve weaving at both ends of the connector, users must analyze each weaving section separately. Cal-B/C allows users to enter data for both roads using the macro that prepares data for a second road. This macro had been available previously for interchange and bypass projects. The macro has been modified to also accommodate freeway and HOV connectors.

Impacts Analyzed

The impacts analyzed by Cal-B/C include changes in:

- Travel time
- Vehicle operating costs
- Emissions
- Safety.

User Inputs

- For weaving improvements, users are able to input speed and volume data for traffic in the weaving section using the output of simulation models. These data should be entered into the "Model Inputs" section of Cal-B/C.

- Although the use of simulation model data is the preferred approach, the model can also estimate speed changes due to weaving using simple rules of thumb. The model calculates the without project speeds using a lookup table based on the simulations conducted in Texas by

Fitzpatrick, Brewer, and Vengler (2003). The average speed data in the original table have been converted to percent reductions in speed.

	Freeway Connectors
0.000	1.00
0.002	0.98
0.004	0.96
0.006	0.95
0.008	0.93
0.010	0.91
0.012	0.89
0.014	0.87
0.016	0.85
0.018	0.84
0.020	0.79
0.022	0.75
0.024	0.71
0.026	0.66
0.028	0.62
0.030	0.58
0.032	0.54
0.034	0.50
0.036	0.48
0.038	0.47
0.040	0.47
0.042	0.47
0.044	0.47
0.046	0.46
0.048	0.46
0.050	0.46
0.052	0.46
0.054	0.45
0.056	0.45
0.058	0.45
0.060	0.45
0.062	0.45
0.064	0.45
0.066	0.45
0.068	0.45
0.070	0.45
0.072	0.45
0.074	0.45
0.076	0.45
0.078	0.45
0.080	0.45

Adapted from: Fitzpatrick, K., Brewer, M.A., and Vengler, S.P., Managed Lane Ramp and Roadway Design Issues, Texas Transportation Institute, Report Number 4160-10, January 2003.

- Users must enter a *percentage of traffic on the highway that is affected by weaving*. The model provides a default of 2.5 percent, which is based on the simulations run by Fitzpatrick, Brewer, and Vengler. The user can modify this percentage if better data area available.

- For geometric corrections, users must enter the *before and after design speeds* for the project as the actual speeds. These adjustments can be made on the "Model Inputs" page of Cal-B/C.

- For weaving improvements, the model also includes a *safety improvement factor* on the "Model Inputs" sheet. The default is set to 0 percent, but it can be changed by users. For geometric corrections, users must enter the *statewide accident rates* by accident type for the before and after facility types.

Impact Calculation

- **Travel time** impacts are estimated from the before and after speeds. For weaving sections, these speeds may be inputted by the user from a simulation model or estimated using the lookup table and the *percent weaving*. If the lookup method is used, the lookup table is used for the without project case. With project speeds are estimated using the standard Cal-B/C method (BPR curve). This assumes that the new freeway connector corrects the weaving problem. If this is not the case, the user must adjust the speeds in the with case.

- Unlike auxiliary lanes, traffic is not separated into weaving and non-weaving vehicles since all vehicles on the highway are impacted by weaving. (The percent weaving represents the number of vehicles initiating weaving movements that impact every other vehicle on the highway.)

- For geometric corrections, the speeds are inputted by the user on the basis of design speeds.

- Cal-B/C estimates **Emissions** and **vehicle operating cost** benefits from the change in before and after speeds. The rates do not change.

- For weaving improvements, **Safety** benefits are calculated using the safety improvement factor. Since the default is set to 0 percent, most projects will not have safety benefits. However, users can override this default value if project-specific information or more up-to-date research is available.

- For geometric corrections, safety benefits are calculated from statewide accident rates associated with the before and after facility types.

Major Assumptions

- The speed lookup table is based on limited data using a VISSUM model in Texas. Users are strongly encouraged to use simulation data whenever available.

- The freeway connector is assumed to correct any weaving problems.

5.4 HOV Connectors

HOV connectors are similar to general freeway connectors, except that only HOVs can use them. Cal-B/C analyzes HOV connectors in a manner similar to that for freeway connectors that improve weaving.

As with freeway connectors, users must analyze each weaving section separately for HOV connector projects that improve weaving at both ends of the connectors. Cal-B/C allows users to enter data for both sections using the macro that prepares data for a second road.

Impacts Analyzed

The impacts analyzed by Cal-B/C include changes in:

- Travel time
- Vehicle operating costs
- Emissions
- Safety.

User Inputs

- The inputs for HOV connector projects are similar to those for freeway connector projects that improve weaving.

- However, users must also enter the *HOV lane volume* and the *average vehicle occupancy (AVO) restriction* for HOV lanes to estimate benefits correctly.

- Users must also provide the *percent of HOV traffic* that connects between the two highways in the analysis. As with general freeway connectors, users must analyze the impacts on each freeway separately and add the benefits, but make sure not to count benefits and costs twice.

Impact Calculation

Cal-B/C estimates benefits for HOV connectors similar to those for freeway connectors that improve weaving conditions, but with the following changes:

- As with freeway connectors, the use of detailed micro-simulation data is the preferred approach. However, rule of thumb data are also provided in a lookup table. The lookup table for freeway connectors also includes a column for HOV connectors and HOV drop ramps:

	HOV Conn. and Drop Ramps
0.000	1.00
0.002	0.99
0.004	0.98
0.006	0.96
0.008	0.95
0.010	0.94
0.012	0.93
0.014	0.92
0.016	0.90
0.018	0.89
0.020	0.88
0.022	0.87
0.024	0.85
0.026	0.84
0.028	0.82
0.030	0.79
0.032	0.76
0.034	0.73
0.036	0.71
0.038	0.68
0.040	0.65
0.042	0.62
0.044	0.60
0.046	0.57
0.048	0.54
0.050	0.51
0.052	0.48
0.054	0.48
0.056	0.47
0.058	0.47
0.060	0.47
0.062	0.47
0.064	0.47
0.066	0.47
0.068	0.46
0.070	0.46
0.072	0.46
0.074	0.46
0.076	0.46
0.078	0.46
0.080	0.45

Adapted from: Fitzpatrick, K., Brewer, M.A., and Vengler, S.P., Managed Lane Ramp and Roadway Design Issues, Texas Transportation Institute, Report Number 4160-10, January 2003.

- Users should enter the percent weaving as the percentage of HOV traffic that is weaving (i.e., using the HOV connector). The model provides a

default value of 4 percent. This is based on the research conducted by Fitzpatrick, Brewer, and Vengler.

• The model separates the weaving HOV traffic from the other HOV traffic, so that the benefits can be estimated separately. The weaving HOVs are treated in the model as "weaving vehicles," while the other HOVs are treated as "HOVs." However, the **travel time** benefits for both groups are calculated using the appropriate AVO for HOVs.

• The weaving affects both the weaving HOVs ("weaving vehicles") and the other vehicles on the mainline freeway. The speeds calculated from the lookup table are used for weaving vehicles and non-HOVs. Speeds for HOVs (those that remain in the HOV lanes) are calculated using the standard BPR curve in Cal-B/C.

• **Vehicle operating cost** and **emissions** benefits are calculated as they are for freeway connectors.

• **Safety** benefits are estimated using the change in connector types (if one occurs), since HOV-specific rates are not available.

Users can enter detailed speed and volume data if available from simulation models or detailed studies.

Major Assumptions

• The speed lookup table is based on limited data using a VISSUM model in Texas. Users are strongly encouraged to use simulation data whenever available.

• Cal-B/C assumes that all HOVs connecting between freeways use the HOV connector.

• The model ignores any positive or negative impact of the HOV lane on through HOV traffic.

• Cal-B/C ignores the impact on existing freeway connectors caused by diverting HOVs to HOV connectors.

5.5   HOV Drop Ramps

HOV drop ramps function similarly to HOV connectors, except that they allow HOV lane users direct access on and off the freeway rather than direct access to another HOV lane. Cal-B/C model HOV drop ramps using the same methodology as HOV connectors. Each side of the freeway and each on-ramp and off-ramp are analyzed as

separate projects. Benefits and costs can be summed across projects if users want a benefit-cost ratio for the full set of projects.

Impacts Analyzed

The impacts analyzed by Cal-B/C include changes in:

- Travel time
- Vehicle operating costs
- Emissions
- Safety.

User Inputs

The user inputs for HOV drop ramps are the same as for HOV freeway connectors, except that users must provide the *percent of HOV traffic* exiting or entering the freeway that rather than the percent of HOV traffic connecting between highways.

Impact Calculation

Cal-B/C calculates the benefits of HOV drop ramps similar to those for HOV freeway connectors. Users can also enter detailed speed and volume data on the "Model Inputs" sheet if these data are available from simulation models or detailed studies.

Major Assumptions

- The speed lookup table is based on limited data using a VISSUM model in Texas. Users are strongly encouraged to use simulation data whenever available.

- Cal-B/C ignores the impact on existing general purpose on-ramps and off-ramps caused by diverting HOVs to HOV drop ramps.

- The model also ignores any impact HOV drop ramps have on HOV through traffic.

- The model assumes that all HOVs entering or exiting the highway use the HOV drop ramps.

5.6   On-Ramp Widening

Cal-B/C estimates the benefits of on-ramps widening as improving the quality of ramp metering. Widened on-ramps provide increased storage facilities for vehicles waiting for ramp meters and reduce the chance of ramp metering benefits being reduced by queue control strategies.

The benefits of on-ramp widening are estimated by calculating first the benefits of ramp metering along the corridors. These benefits are then multiplied by the percent improvement in metering quality to determine the benefits due to on-ramp widening.

Impacts Analyzed

The impacts analyzed by the recommended framework include changes in:

- Travel time
- Number of accidents
- Vehicle operating costs
- Emissions.

User Inputs

Users must input the same information as for a ramp metering project. In addition, users must enter:

- *Hourly ramp volume* – Users need to enter the average hourly volume for the on-ramp during the peak period in vehicles per hour. This volume is used to determine the quality of ramp metering.

- *Cars per green signal* – Users must also input the number of cars that are allowed per each green of the ramp meter signal. This is also used to determine the quality of ramp metering.

 Impact Calculation

The benefits of increase storage capacity are estimated as the benefits of the ramp metering strategy on the corridor lost due to inefficient ramp metering and queue control:

- Cal-B/C first estimates the benefits of ramp metering on the corridor using the methodology outlined for ramp metering. The benefits are estimated using the same methodology as used in the Caltrans TMS Master Plan for upstream adaptive queue control. However, an adjustment is made in the speed and volume adjustment factors. With ramp metering, the project adds ramp metering to a corridor that does not have metering. With on-ramp widening, the corridor already has ramp metering. This metering needs to be "turned off" in the before case, so the factors are reversed.

- The estimated benefits are multiplied by 100 percent minus the percentage of metering availability (metering quality). This percentage

is calculated using a combination of the hourly ramp volume, the number of vehicles per green meter signal, and the relationships presented in Chaudhary and Messer (2000):

Impact of Ramp Demand on the Quality of Ramp Metering
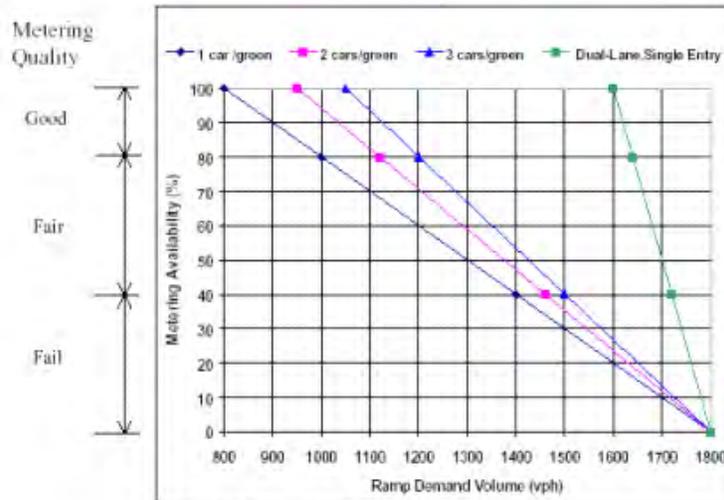
Source: Chaudhary and Messer, 2000.

- The resulting benefits indicate the difference between existing ramp metering and improved ramp metering. As approved by the project Advisory Committee, this difference is presented as the benefit of ramp storage.

Major Assumptions

- The model assumes that the primary reason for widening the on-ramp is to improve the efficiency of ramp metering by reducing the need for queue control.

- It is also assumed that ramp metering already exists on the corridor. If not, the addition of TMS field elements to accommodate ramp metering strategies should be analyzed as a separate project.

- The quality of ramp metering is estimated using a table developed in Texas and may not reflect typical metering rates and strategies in California.

- As for ramp metering, Cal-B/C assumes that the benefits of on-ramp widening occur only during the peak period.

VI. PAVEMENT REHABILITATION

VI. PAVEMENT REHABILITATION

Caltrans developed the Cal-B/C benefit-cost model to assess the cost-effectiveness of capital investments proposed for the State Transportation Improvement Program (STIP). As part of an interim update completed in 2000, Caltrans investigated ways to enhance the base model so it could consider the benefits of projects included in the State Highway Operation and Protection Program (SHOPP). For the interim update, Caltrans considered only changes required to incorporate roadway rehabilitation projects into Cal-B/C because roadway rehabilitation had traditionally been the largest SHOPP program element in terms of funding. The latest updates that incorporate TMS projects and operational improvements expand the Cal-B/C model to incorporate most of the other types of projects included in the SHOPP.

As of the interim update, the roadway rehabilitation program element of the SHOPP was made up of seven project types: [26]

- *Roadway (Pavement) Rehabilitation*: Projects with a primary purpose to rehabilitate roadways that ride rougher than established maximums or exhibit substantial structural problems. As a secondary purpose, projects may include rehabilitation of appurtenances that are failing, worn out or functionally obsolete.

- *Long-Life Pavement*: Projects which implement longer-life pavement rehabilitation on roadways where the average daily traffic is greater than 150,000 vehicles and/or average daily truck volume is greater than 15,000 vehicles.

- *Bridge Rehabilitation*: Projects that restore or replace structures when they become inadequate. Included are strengthening to meet permit loadings, rehabilitation of bridge decks and deck joints, replacement of non-standard bridge railing, and work needed to meet standards required under CAL-OSHA.

- *Bridge Scour*: Projects that restore or replace bridges with footing scour problems in stream beds.

- *Major Damage Restoration*: Projects that provide emergency and/or permanent repairs in response to natural disasters, catastrophes, or

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[26] *Note that one project type shares the name of the program element. This project type, roadway rehabilitation, is referred to as pavement rehabilitation in the rest of the document.*

events such as storm damage, floods, fires, earthquakes, or volcanic action. Snow removal, ice control and other minor maintenance activities are not included.

- *Roadway Protective Betterments*: Projects that extend the useful life of the state highway system by adding facilities that were not anticipated at the time of initial construction. They protect the highways by adding new facilities that prevent damage from flooding, slipouts, slides or other physical forces. This project types was included in the Operations category in the previous SHOPP plans.

- *Hazardous Waste Cleanup*: Cleanup of hazardous waste contamination on state highway and other department-owned property (site is not part of a programmed STIP, SHOPP, or Minor Project).[27] (2000 Ten-Year State Highway Operation and Protection Plan).

This section outlines the changes made to the Cal-B/C model to accommodate roadway rehabilitation projects related to pavement. Modifications were considered, but not made, for three other types of roadway rehabilitation projects (i.e., long-life pavement, bridge rehabilitation, and bridge scour). Long-life pavement projects were determined to be more appropriately analyzed using life-cycle cost estimation rather than a user-cost framework and should be analyzed outside of Cal-B/C. Bridge rehabilitation and scour projects generally result in structural, rather than functional, improvements. Projects that result in functional improvements, which can be analyzed in a user-cost framework, are less common and funded outside the SHOPP.

The remainder of this section describes pavement rehabilitation projects and is organized as follows:

- Theoretical Background
- Factors Related to Pavement Rehabilitation
- Methodologies in Use
- Caltrans Methodology.

The references section lists all the documents consulted in developing the Cal-B/C modifications to incorporate pavement rehabilitation projects.

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[27] *2000 Ten-Year State Highway Operation and Protection Plan.*

1.0   THEORETICAL BACKGROUND

Several frameworks[28] are available for analyzing the cost effectiveness of transportation projects. While some methods take an engineering economy perspective, others follow an economic utility approach. The two methods most frequently used for the analysis transportation projects are life-cycle cost analysis and benefit-cost analysis. Life-cycle cost analysis considers agency costs (including construction, operating and maintenance) associated with owning a particular transportation facility over its economic life. Benefit-cost analysis focuses on facility impacts and compares the annual benefits realized by users of the facility and/or society to the annual costs of constructing, operating, and maintaining the transportation facility. Life-cycle cost analysis is typically used by transportation engineers in selecting appropriate preliminary designs or when users benefits are difficult to measure directly. This paper focuses on the benefit-cost analysis.

Highway users generally incur costs when traveling. Whenever transportation projects reduce costs for users, they produce user benefits. Transportation agencies frequently examine the reduction in user costs when running benefit-cost models for transportation projects. Benefit-cost models typically consider four categories of user costs:

- Travel Time
- Vehicle Operating Costs
- Accident Costs
- Environmental Costs.[29]

Benefit-cost models calculate the changes in user costs generated by transportation improvement projects. Changes in user costs are converted to dollar values and then compared to the costs of the improvement project itself, thereby generating benefit cost ratios and allowing for an economic evaluation of transportation system improvements.

Measuring benefits from the user-cost perspective is easier for capacity-enhancing projects than for other types of improvements. In recent years, theoretical research has begun to focus on benefit-cost analysis for maintenance and system preservation projects, such as the pavement projects included in the SHOPP. Historically, analysis of such projects has focused on agency life-cycle costs – overall reduction in costs over the life of the project. The challenge considered is to capture user benefits using a user-cost framework.

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[28] *Examples include life-cycle cost analysis, benefit-cost analysis, break-even analysis, payback period, and capital cost.*

[29] *Environmental costs are sometimes considered to be societal, rather than user, benefits, but the analysis framework is similar.*

Pavement rehabilitation projects consist of improving deteriorating pavement. Caltrans has recently shifted its focus from a "worst-first" to a preventive maintenance strategy that emphasizes long-term pavement performance and reduces overall rehabilitation costs. In addition, the Department has begun to examine applications for longer-life pavement, particularly on roadways with high traffic volumes (average daily traffic > 150,000 or average daily truck volume > 15,000). While the benefits of long-life pavement are still being considered, it is anticipated that long-life pavement will further contribute to a more cost-effective rehabilitation program.

2.0   FACTORS RELATED TO PAVEMENT REHABILITATION

Overall, the rehabilitation of roadways should have positive impacts on motorists - smoother highways lead to better ride quality, faster speeds, and less wear and tear on vehicles. Most of these impacts occur as a result of improvements (or decreases) in road roughness.

Pavement rehabilitation projects include both "resurfacing" and "rehabilitation" of a roadway. Both projects imply altering the surface, or pavement condition, of the roadway, but rehabilitation is more extensive having a strengthening or shape correction component beyond altering the surface characteristics of the roadway.[30] However, the impacts on user costs of both project types are generated by changes in the surface condition (roughness) of the roadway making the distinction between resurfacing and rehabilitation a needless one from a user-cost perspective.[31] For purposes of this discussion, resurfacing and rehabilitation are used interchangeably.

Traffic engineers recognize that pavement quality is affected by a number of complex factors. As maintaining structural integrity is their primary goal, engineers focus on distress mechanisms that lead to <u>structural failure</u>. Such distress mechanisms vary by surface composition. Typical forms of distress mechanisms for pavement include:

- Fatigue cracking
- Rutting
- Thermal cracking.

Of these three, fatigue cracking is typically considered to be the major distress. Concrete has its own set of distress mechanisms, which include fatigue cracking and faulting. Engineers can measure distresses using a variety of qualitative and quantitative techniques, such as deflection testing.

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[30] *Infrastructure Department, World Bank.*

[31] *However, the difference in cost between the two project types will have a significant impact on the cost component of the Cal-B/C generated benefit cost ratio.*

While the measurement and correction of distress mechanisms is critical for maintaining structural integrity for highway surfaces, users are more concerned about functional failure. Structural measures do not necessarily capture the ride quality of traveling over the roadway or the user benefits generated by improvements to the pavement.

Empirical research on the impact of road rehabilitation on travel time savings and other user benefits has focused on the concept of road roughness. Road roughness affects travel time and thus travel time savings by affecting the speed of travel over a roadway. In general, the greater the roughness of the road, the slower the speed of travel over the segment.

Until the mid-1980s, road roughness was measured in different ways and presented in different units by governments and agencies around the world. In 1982, the World Bank initiated the International Road Roughness Experiment (IRRE) in Brazil to compare the various measures of road roughness and to develop a single standard for calibration of these measures. The International Roughness Index (IRI) was the outcome, and is defined as the number of inches (or meters) of surface roughness (or unevenness) per mile (or kilometer) of pavement. A perfectly level road surface would have an IRI of 0 m/km, a moderately rough paved road would have an IRI of about 6 m/km, increasing up to about 20 m/km for extremely rough unpaved roads (Paterson, 1987). Beginning in 1990, the Federal Highway Administration (FHWA) required states to report road roughness using the IRI scale for inclusion in their Highway Performance Monitoring Systems (HPMS). Unlike their oversees counterparts, who express IRI in m/km, US states generally report IRI in inches/mile.

Road roughness describes not only a physical aspect of the roadway and the physical effects on vehicles (through the suspension), but also a subjective aspect of ride quality for vehicle operators and passengers. By describing the effect on vehicle occupants and the wear on the vehicle, IRI considers all three elements – the road profile, the vehicles, and vehicle occupants (Paterson, 1987). Road roughness, as used in this discussion, is defined according to the IRI scale, capturing road profile, vehicle, and occupancy effects.

As the next sections show, road roughness plays a central role in measuring benefits in all categories of user costs.

2.1   TRAVEL TIME SAVINGS

Highway investments and other transportation infrastructure projects often lead to higher speeds and lower travel times for drivers, passengers, and freight. Pavement rehabilitation projects tend to lower travel times through improvements in road roughness. Lower travel times are ultimately user benefits that can be converted into dollar terms using the value of time. The value of time is affected by a number of

factors including wage rates, trip purpose, time saved as well as disutility costs (i.e., the general level of discomfort or other negative aspect associated with time lost due to travel). 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 value of time is further described in the Caltrans technical issue paper on the value of time.[32]

Prior to the development of the IRI, the American Association of State Highway Officials (AASHTO) published *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements* (1977). This "Red Book" recognized that roadway quality impacts user benefits, particularly vehicle operating costs. However, at the time, there was no useful way to generalize the wide variation in pavement conditions to assess with any level of accuracy the effects of pavement condition on operating costs. Instead, the "Red Book" provided an adjustment factor to be applied directly to vehicle running costs on paved roads to arrive at estimated costs for unpaved roads. Since the publication of this manual, however, most road surface characteristics that impact vehicle operating costs and speeds have been captured in a single measure – the IRI.

Several researchers have examined the effect of road roughness (as captured by IRI) on vehicle operating speeds. Using the database developed in the IRRE, researchers for the World Bank developed aggregate-mechanistic[33] models to assess the vehicle speed and operating costs associated with various travel conditions.[34] As shown in Exhibit VI-1, Paterson and Watanatada (1985) found that free-flow vehicle operating speeds increase only if road conditions improve drastically. Slight changes in road conditions for roadways with low roughness levels (IRI ≤ 4 m/km) do not significantly impact travel speeds.

As shown in Exhibit VI-1, Paterson and Watanatada found that free-flow vehicle operating speeds remain virtually unchanged up to IRI levels of 4 m/km. Above 4 m/km, free-flow speeds fall almost linearly as IRI increases. A general rule of thumb is that the product of speed (in km/h) and roughness (in m/km IRI) rarely exceeds 700 for cars or 550 for heavy trucks.[35] In other words, the effect of road roughness on vehicle speed is greater for heavy trucks than it is for cars. This finding suggests that travel time savings are generally larger for trucks than for cars. Since the value of time for trucks is generally larger than it is for cars, this effect is compounded.[36]

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[32] *Caltrans Transportation Planning Program, Cal-BC Users Manual Technical Supplement – The Value of Time, 1999*

[33] *Mechanistic models are based on the laws of motion and a simplified representation of engine performance.*

[34] *Watanatada and others, 1987. The IRRE research led to the development of the World Bank's HDM-III user-cost model.*

[35] *Paterson, pg. 14.*

[36] *For more details on the value of time, see the Cal-BC Users Manual Technical Supplement.*

Exhibit VI-1
**Influence of Road Roughness on Vehicle Speed**
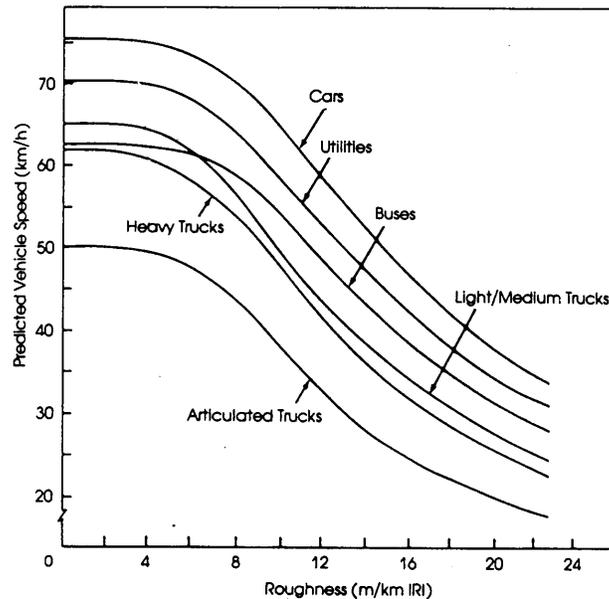
Source: Paterson (1989), reprinted from Paterson and Watanatada (1985)

The applicability of World Bank models to advanced highway systems has recently been called into question by a number of authors (Lewis and others, 1999 and McLean and Foley, 1998), who point out that empirical data for this research was derived from tests on unpaved roads. World Bank models are likely to overestimate the effects of roughness on travel speeds for paved roads that are found in developed countries, such as the United States.

McLean and Foley (1998) provide results of additional research conducted in Australia during the mid-1990s. This field research (Botteril 1996, 1997), sponsored by ARRB Transport Research,[37] finds that the impacts of roughness on cars on paved roads to be less than the earlier World Bank research on unpaved roads. As shown in Exhibit VI-2, car speed remains constant up to an IRI of about 5 m/km, dropping only slightly as IRI increases to 7 m/km. Results similar to that depicted in Exhibit VI-2 were found for articulated trucks with operating speeds remaining fairly constant for IRI values up to 4 m/km.

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[37] *Formerly called Australian Road Research Board*

Exhibit VI-2
Influence of Road Roughness on Vehicle Speed
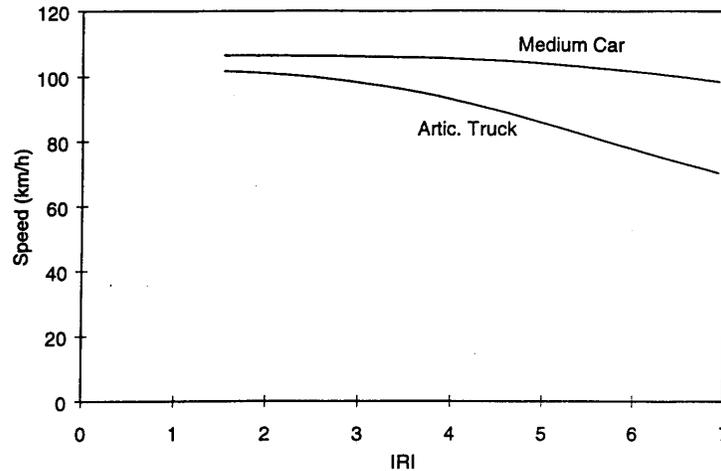
Source: McLean and Foley (1998).

The more recent Australian research also reflects vehicle design improvements since the time of the IRRE experiments, indicating that vehicles are somewhat more roughness tolerant today. However, the critical difference with respect to the relationship between road roughness and operating speeds for cars and trucks is still valid today. Trucks are more sensitive to road roughness.

The basic relationship between road roughness and speed is an important one for the analysis of the effects of road roughness on the remaining user-cost categories as well. Vehicle operating speed is a key variable in determining vehicle operating costs through the effects of speed on fuel consumption. Generally speaking, an increase in vehicle operating speed results in an increase in accident rates and an increase in emissions.

2.2 VEHICLE OPERATING COSTS

As described in the *Cal-B/C User's Manual Technical Supplement Volume 1*, vehicle operating costs are made up of four primary components:

- Fuel consumption
- Tire/maintenance costs
- Depreciation
- Insurance.

Roadway rehabilitation projects generally do not affect the last two components. The possibility of severe roughness causing excessive wear and tear on a vehicle could effectively increase depreciation costs by lowering the effective service life of the vehicle. However, such conditions are extreme and generally not characteristic of the

California highway system. Minor wear and tear costs caused by moderately worn pavements are captured in the tire and maintenance cost category. Insurance tends to be a function of general accident rates, driving records, and miles driven. Pavement rehabilitation projects tend to influence neither these factors nor insurance rates.

We now describe each of the first two components.

Fuel Consumption

Poor pavement quality affects fuel consumption in three ways:

- Lower average speeds
- More fuel consumed to maintain a constant speed
- Speed cycling.

The first factor (the effect of pavement quality on vehicle operating speeds) has already been described in the travel time savings section. As road roughness causes speeds to change (Paterson, 1985 and Botteril, 1996 and 1997), fuel consumed varies according to traditional operating speed/fuel consumed relationships.[38] These relationships are typically already captured in benefit-cost models that focus on traditional capacity expansion projects.

The second factor captures the impacts of roadway surface texture on the rolling resistance of vehicles over a roadway. Surface texture is a description of the longitudinal characteristics, or surface deviations, of the roadway and is measured in wavelengths. Also associated with surface texture is texture depth, which is the vertical distance between the amplitude of the wavelength and the roadway surface. Both concepts are depicted in Exhibit VI-3.

Exhibit VI-3
Surface Texture and Texture Depth

a = wavelength
b = texture depth

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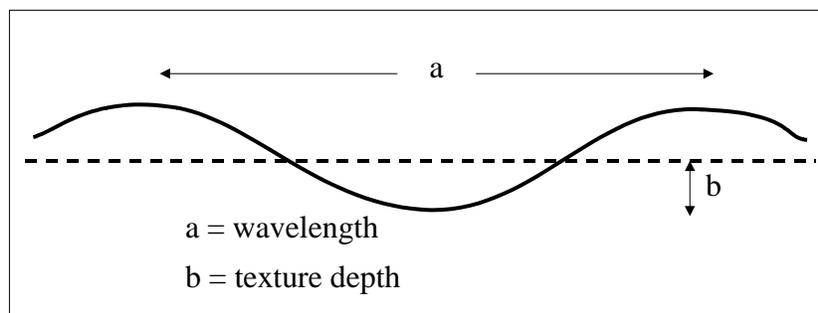
[38] *For more details on vehicle operating costs, see Caltrans technical issue paper.*

When road surface characteristics are given labels as in Exhibit VI-4, roughness is an extreme form of surface texture that exhibits wavelengths greater than .5m. Roughness, in this sense, reflects an extreme state of road surface texture. However, the term roughness as reflected in IRI is a more complete concept that includes the range of surface characteristics over which vehicle suspension systems are affected by surface texture (McLean and Foley, 1998 & UMTRI, 1998).
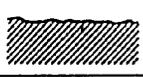
Exhibit VI-4
Road Surface Characteristics

	Wavelength
	< 0.5mm
	0.5 – 50mm
	50 – 500mm
	0.5 – 50m

Source: McLean & Foley (1998), from PIARC Specifications

It is possible for two or more levels of surface texture to exist at the same time. Both long and short wavelength can coexist on single piece of pavement as shown in Exhibit VI-5.

Exhibit VI-5
Surface Texture

Surface		Scale of texture	
		Macro	Micro
A		rough	harsh
B		rough	polished
C		smooth	harsh
D		smooth	polished

Source: Kennedy et. al, 1990.

Surface texture increases rolling resistance and thus fuel consumption through energy losses in the tire while roughness increases rolling resistance and thus fuel consumption through energy losses in the suspension (McLean & Foley, 1998).

Research has been conducted on the relationship between both surface texture and roughness on fuel consumption.

There have been a number of studies that have attempted to document the effect of road roughness on fuel consumption. They were summarized in an exhaustive review by McLean and Foley (1998). The studies examined are summarized in Exhibit VI-6.

There are essentially two methods employed for these studies:

- Direct measurement of fuel consumption
- Measurement of rolling resistance.

Comparing rolling resistance on a range of paved surfaces, Descornet found that a five-percent change in rolling resistance represents about a one-percent change in fuel consumption (Descornet 1990b). The corresponding factor for loaded trucks is four percent. These factors were used to convert results reported in terms of change in rolling resistance to change in fuel consumption.

With the exception of Watanatada et al (1987) and du Plessis et all (1990), all other studies were carried out on paved roads and cover ranges of roughness that can be expected on a surfaced network. Study results come from research conducted in Wisconsin, United Kingdom, France, Belgium, and Sweden. Since fuel economy has generally improved over time, findings from later studies are generally considered more valid.

The majority of research considered the effects of roughness on rolling resistance (or fuel consumption) for cars only. Excluding the two studies conducted on unpaved roads, only one considered the effects on trucks. This study, conducted by Young (1988), did not report results in terms of IRI. In addition, McLean and Foley (1998) have questioned the factor used to convert to IRI, because the effects of roughness on fuel consumption were so much higher for this study than any of the others.

The FHWA and the National Cooperative Highway Research Program (NCHRP) recently funded an accelerated pavement test to examine how material and construction variations affect pavement performance. Although it was not the original intent of pavement test, the WesTrack project provided more up-to-date information on how pavement roughness affects fuel consumption for trucks. As part of the experiment, four driverless trucks traveled over pavement test sections during a 2.5-year period for a total of over 1.3 million kilometers (820,000 miles). When researchers compared fuel consumption before and after a major pavement rehabilitation, they found that an average IRI change of about 10 percent led to a 4.5 percent change in fuel consumption (FHWA Transporter, June 2000). These findings generally corroborate those of McLean and Foley (1998) on the effect of pavement quality on truck fuel consumption.

Exhibit VI-6
Summary Results from Studies of the Effect of Roughness on Fuel Consumption – Constant Speed

				Change per Unit of IRI	
					Fuel Consumed
Young (1988)	Coast down – artificial roughness Direct fuel measurement – artificial roughness Direct fuel measurement – vehicles side by side Direct fuel measurement – range of surfaces *On paved roads*	1.3 to 4.0 3.3 to 5.6 2.3 to 4.4 1.7 to 5.4	Truck Car Car Car		4.1 3.1 3.6 0.8
Ross (1982)	Direct fuel measurement – range of surfaces *On paved roads*	0.5 to 3.7	Car		0.4
Bester (1984)	Rolling resistance – range of surfaces *On paved roads*	1.4 to 5.5	Car	2.6	0.5
Descornet (1990)	Rolling resistance – range of surfaces *On paved roads*	0.8 to 7.7	Car	4.0	0.8
Laganier and Lucas (1990)	Rolling resistance – range of surfaces *On paved roads*	1 to 6 (estimated range)	Car	6.0	1.2
Sandberg (1990)	Direct fuel measurement – range of surfaces *On paved roads*	1 to 6	Car		1.7
du Plessis et al (1990)	Rolling resistance – range of surfaces *On unpaved roads*	1.2 to 15	Car Truck	3.4 4.4	0.7 1.1
Watanatada (1987)	Rolling resistance – range of surfaces *On unpaved roads*	2 to 14	Car Truck	2.5 1.8	0.5 0.5

Source: McLean and Foley (1998)

Rough surface texture has also been shown to have a negative effect on fuel consumption through increased rolling resistance and energy losses in the tires. A comprehensive collection of research on the subject is contained in "Surface Characteristics of Roadways: International Research and Technologies" (1990) and "Vehicle-Road Interaction" (1994), both published by the American Society for Testing and Materials.

Some recent research has suggested that the effect of pavement condition on fuel consumption is negligible. A study conducted by the Texas Transportation Institute as part of the development of the MicroBENCOST model found fuel consumption to be insensitive to pavement condition but not to surface type (NCHRP, Introduction to StratBENCOST Version 1.0). This suggests that rolling resistance generated by the tires due to surface texture does effect fuel consumption while rolling resistance created through the suspension due to roughness does not. However, the recent WesTrack study (FHWA Transporter, June 2000) runs counter to these findings.

The third factor in the effect of pavement quality on vehicle operating costs in speed cycling (rapid fluctuations in speed). Poor pavement quality tends to increase speed cycling as motorists try to avoid bad pavement and potholes. The effects of speed cycling, as affected by pavement condition, are generally ignored by most benefit-cost models currently in-use, which assume constant running speeds.[39] As a result, fuel consumption may be under-estimated at extreme roughness levels (McLean and Foley, 1998).

Tire and Maintenance Costs

There have been a number of studies that document the effect of road roughness on tire and maintenance costs. McLean and Foley (1998) summarize them in an exhaustive review. The studies examined are summarized in Exhibit VI-7.

As noted by McLean and Foley (1998), most of the research has been conducted on unpaved roads or compared paved to unpaved conditions, like the work found in the ASSHTO Red Book. These results of most research, summarized in Exhibit VI-7, generally apply to extreme roughness conditions.

The studies summarized used two methods to measure tire and maintenance costs:

- Vehicles (including test vehicles, which may not reflect true driving conditions)
- User surveys (while reflecting "real conditions," are difficult to validate and are subject to response bias).

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[39] *Speed cycling due to congested conditions is captured in benefit-cost models such as StratBENCOST.*

The study results presented in Exhibit VI-7 show a wide range of tire and maintenance costs. Tire wear costs grow from 12 to 113 percent per unit increase in IRI and maintenance costs grow from 22 to over 100 percent. Truck costs were shown to be similar in magnitude to those for cars with the exception of the Kenya study.

Engineers at the Chrysler Corporation have examined the effect of pavement conditions on other aspects of vehicle maintenance costs. A 1992 study examined the effect on vehicle suspension fatigue and found that suspension costs are generally not affected until pavement conditions deteriorate substantially (IRI greater than 4 m/km). (Poelman and Weir, 1992)

While the empirical research shows wide variations in the effect of pavement condition of vehicle operating costs for paved roadway networks, some patterns do emerge. Generally, vehicle operating costs are negatively impacted by poor pavement. These impacts do not appear until pavement conditions are poor (IRI greater than 3 m/km or 4 m/km). When the effect of pavement quality on vehicle operating costs is considered in benefit cost models, most models hold operating costs constant for the first few IRI levels. For example, the World Bank HDM-III model holds maintenance costs constant for IRI levels up to 3 m/km.

The FHWA and NCHRP WesTrack accelerated pavement test has also documented the impact of pavement quality on the frequency of vehicle mechanical problems. After comparing truck maintenance before and after a major pavement rehabilitation, researchers found the rehabilitation led to a significant reduction in the frequency of fatigue failures in truck components, such as trailer frames and springs. The study did not quantify the user costs associated with this reduction in failures (FHWA Transporter, June 2000).

2.3 ACCIDENT COSTS

The costs that users incur due to highway accidents can be broken into two components: the exposure of users to accidents (i.e., the accident rate), and the user costs associated with individual accidents. The calculation of costs associated with individual accidents is described Volume 1 of the Technical Supplement to the Cal-B/C User's Guide.

The rest of this section discusses the impact of roadway rehabilitation projects on accident rates.

Exhibit VI-7
Summary Results of Empirical Studies Relating Vehicle Maintenance and Tire Costs to Road Roughness

					Change per Unit of IRI	
						Tire Wear
Hide et al (1975)	Kenya	User survey. Vehicles operated on range of road types and conditions	3.3 to 8.5 3.3 to 8.5	Car Truck	80 24	113 9
Hide (1982)	Caribbean	User surveys. Vehicles operated on different networks of poor quality surfaced roads	4.6 to 9.5 4.6 to 9.0	Car Truck	>100 >100	60 11
Watanatada et al (1987)	Brazil	User survey. Vehicles operated on range of road types and conditions	2 to 18 2 to 18	Car Truck	22 22	12
du Plessis and Meadows (1990)	South Africa	Test vehicles operated on paved and gravel roads	2.7 to 5.8	Car	46	29
Finlayson and du Plessis (1991)	South Africa	User survey. Vehicles operating on range of road types and conditions.	3.1 to 11.5	Truck	45	23

Source: McLean and Foley (1998)

Benefit-cost models typically capture the impact of highway projects by examining the change in average accident rates due to changes in facility type. Empirically derived average accident rates are calculated for each kind of facility defined by factors such as the number of lanes, highway type, geographic location, and average speed. As highway projects change the facility type, different average accident rates are applied. For example, projects that widen lanes tend to decrease accident rates. Pavement quality is typically not a factor considered in defining facility types. As a result, pavement projects do not change the type of highway facility and standard benefit-cost models do not capture the impact of pavement quality on accident rates. Another methodology must be considered.

The research regarding road roughness and accident rates has tended to focus on vehicle speeds and the skid resistance level of the roadway. Generally, improving the skid resistance of a roadway leads to a decrease in accident rates, while increased vehicle speeds raise accident rates. However, the effects of increased skid resistance and speed on accident rates differ for wet and dry roads due a variety of factors described later. The relationship between skid resistance and wet roads is described first, since the majority of pavement accident research has focused on wet roads.

As discussed by McLean and Foley (1998), skid resistance generated between tire and pavement interaction occurs through two mechanisms:

- **Adhesion** occurs as molecular bonds are sheared when tire rubber is pressed into the roadway surface

- **Hysteresis** occurs as a result of energy losses when tire rubber is deformed passing over a roadway surface.

In dry weather conditions, adhesion dominates while the opposite is true on a wet roadway. At low speeds on a wet roadway, water is forced from beneath the tire so that the tire's entire "footprint" is in contact with the road. As speed increases, a wedge of water develops under the tire footprint. As speed continues to increase, water replaces more of the tire footprint on the roadway surface to the point where the tire is no longer in contact with the surface and the vehicle hydroplanes.

A literature review by Kumar (1990) produced the following conclusions regarding the relationship between wet weather, accident rates, and skid resistance:

- Wet weather accident rates are two to three times greater than dry weather rates
- Wet weather accidents account for about 20 to 30 percent of all accidents
- Wet weather accidents are due primarily to skidding so improving the skid resistance of a roadway has the potential to reduce wet weather accident rates.

Skid resistance is a function of roadway microtexture and macrotexture. Microtexture, or the minor surface variations of a roadway, is primarily responsible for hysteretic friction and generates most low-speed skid resistance. As a roadway surface deteriorates (i.e., becomes more polished), microtexture is reduced resulting in reduced skid resistance. Macrotexture allows for water to drain from under the tire. It is primarily responsible for slowing the onset of hydroplaning and general reduction of skid resistance at high speeds. These relationships are shown graphically in Exhibit VI-8.

Exhibit VI-8
**Effects of Microtexture on Skid Resistance**
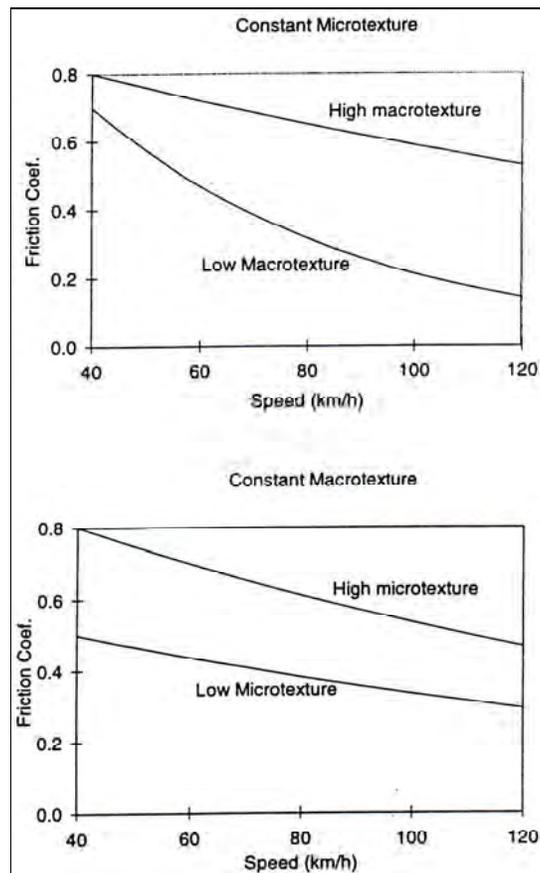
Source: Salt (1977) in McLean and Foley (1998).

As speed increases, the skid resistance (as measured by the friction coefficient) decreases. Both macrotexture and microtexture contribute to this effect.

No standard exists for measuring skid resistance. Accordingly, the results of various studies on skid resistance are difficult to compare, but generally show the same relationships. The PIARC Technical Committee on Surface Characteristics is currently leading an effort to develop an International Friction Index (IFI) similar to the IRI roughness measure (McLean and Foley, 1998).

While the graphs shown in Exhibit VI-8 represent the relationship between skid resistance and speed, a 1984 OECD review examined the relationship between skid resistance and accident rates. Initial studies showed resurfacing projects generally increase skid resistance, lowering accident rates. One study by Harwood et al (1976) included in this review found the relationship between accident rates and skid resistance (as measured by skid number) to be linear as shown in Exhibit VI-9.
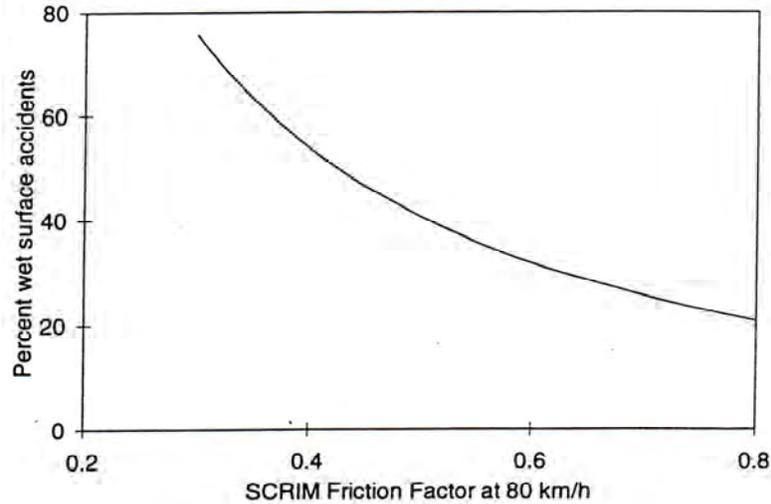
Exhibit VI-9
Linear Relationship Between Accident Rate and Skid Resistance
(at a constant speed)
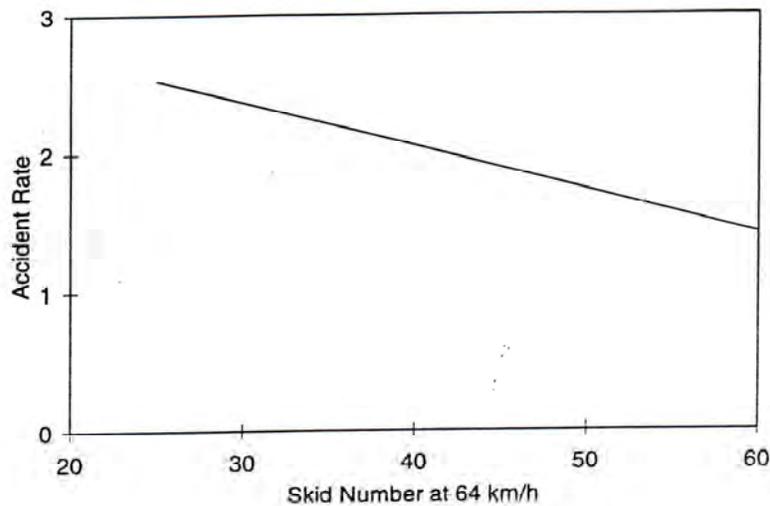
Source: Harwood et al (1976) in McLean and Foley (1998)

However, more recent studies looked at skid resistance on wet roads at high speeds and found a non-linear relationship like that shown in Exhibit VI-10. Produced from studies on high speed German roads, the graph shows that increasing the skid resistance (as measured by the SCRIM friction factor) at low friction values produces larger decreases in the accident rate than at high friction values.

Exhibit VI-10
Non-Linear Relationship Between Accident Rate and Skid Resistance
(at constant speed)

Source: OECD (1984) in McLean and Foley (1998)

Subsequent research in France found results similar to that depicted in Exhibit VI-10. Like the German study, Gothie (1996) found a non-linear relationship between accident rates and macrotexture on wet roads as shown in Exhibit VI-11.

Exhibit VI-11
Surface Texture Depth and Accident Rate
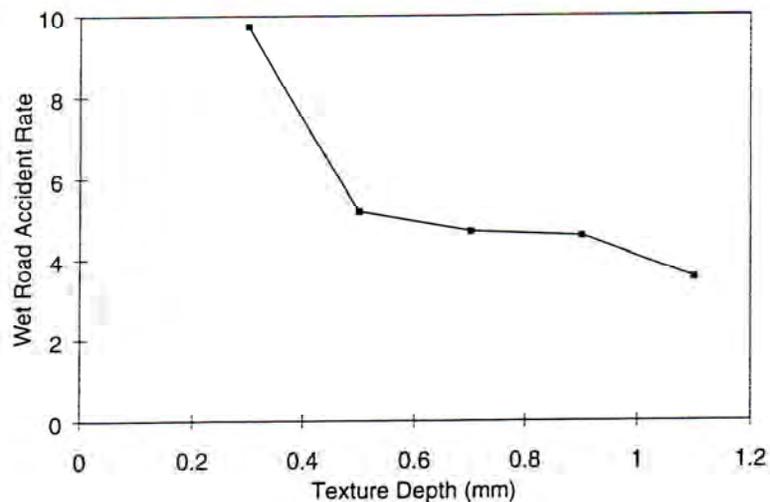
Source: Gothie (1996) in McLean and Foley (1998)

Exhibits Z and A illustrate the importance of macrotexture in generating skid resistance at high speeds. Initial studies were conducted at low speeds and did not fully capture the effect of skid resistance on wet roads, thereby underestimating the impact of skid resistance on accident rates as in Exhibit VI-9. Exhibit VI-9 essentially captured only

microtexture effects of skid resistance - the component captured in the bottom graph in Exhibit VI-8.

In the mid-1970s, the Federal Highway Administration (FHWA) initiated the 3-R (resurfacing, restoration, and rehabilitation) program for non-freeway Federal-Aid systems. As 3-R monies began to be applied to new highways, safety concerns arose over a perceived decrease in safety after 3-R projects. Researchers in the United States started to look comprehensively at accident rates attributable to roadway surfaces after anecdotal evidence that accident rates increased after 3-R projects.[40]

The National Academy of Sciences commissioned a literature review to examine the relationship between resurfacing projects and accident rates. The study, performed by Cleveland (1987) found that, overall, accident rates were increasing, but a distinction existed between wet and dry roads. Accident rates dropped on wet roads after 3-R projects, but increased on dry roads. Exhibit VI-12 summarizes the results of the literature review conducted by Cleveland.

Exhibit VI-12
Accident Rates after Pavement Resurfacing

	Percentage Change in Accident Rate		
			Average Over Project Life
			-7
			+6
			+3

Source: Cleveland (1987) in McLean and Foley (1998)

While the largest impacts were felt immediately following the resurfacing (first year) and were no longer felt by the end of the project (final year of accepted pavement life), the average accident rate went up over the life of the project. Reasons proposed by Cleveland for why dry road accident rates increased include: higher operating speeds and decreased driver attention after pavement resurfacing.

The TOVE (Swedish acronym standing for traffic safety and road surface properties) project in Sweden found results consistent with those documented by Cleveland:

• Slightly worn pavements have lower accident rates than considerably worn pavements in wet weather.

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[40] *3-R refers to the use of federal aid funds for the resurfacing, restoration, and rehabilitation work on non-freeway systems (TRB, 1987).*

- Slightly worn pavements have higher accident rates than considerably worn pavements in dry weather.

- Accident rates overall are higher for slightly worn pavements than for considerably worn pavements.

These results are consistent with the body of research presented here. Slightly worn pavements have greater microtexture than considerably worn pavements contributing to increased skid resistance and thus lower accident rates on wet roads. Faster operating speeds on only moderately worn pavements contribute to higher accident rates on dry roads. As dry weather conditions are likely to predominate over wet weather conditions, overall accident rates are likely to be higher for road surfaces in good condition versus poor condition.

The Cleveland and TOVE studies suggest that the effect of pavement rehabilitation projects on accident rates depends on local climate and mix between dry and wet conditions. In an arid climate, such as that found in California, accident rates are likely to increase due to dry conditions predominating. However, the effect of each project depends on local climate conditions (which must be forecasted over the life-cycle of the pavement project) and the effect is likely to be slight (Cleveland suggests no than a 6 percent change).

Another factor that has not been addressed in the literature is the affect of pavement resurfacing on accident severity. One hypothesis is that the average accident severity diminishes as a result of resurfacing. This hypothesis is based on the assumption that wet-weather accidents tend to be more severe than accidents occurring in dry conditions. However, as Exhibit VI-13 illustrates, recent TASAS data does not support this hypothesis.

Exhibit VI-13
1997 California Accidents in Rain

	Percent Occurring in Rain
	3.8%
	5.4%
	5.3%
	5.3%

Source: 1997 Accident Data on California State Highways, Caltrans

The percentage of fatal accidents occurring in rain is lower than the percentage of other accidents occurring in wet conditions (although slightly more injury accidents do occur). This suggests that lowering the number of accidents occurring in wet conditions does not lower the average accident severity. Pavement projects may have the opposite effect. By increasing average speeds and the number of accidents occurring in dry

conditions, pavement projects may increase average accident severity. More research is needed on the opposite influence of wet and dry conditions on accident severity.

2.4 ENVIRONMENTAL COSTS

Road roughness affects two types of environmental costs, which are described in the sections that follow:

- Vehicle emissions
- Noise generation.

Vehicle Emissions

The theoretical research has generally not considered the effect of pavement improvements on vehicle emissions specifically; however, the change in environmental costs associated with changes in road roughness are due to changes in travel speeds and fuel consumption which lead to changes in emissions levels. It is through travel speed and fuel consumed that environmental costs are incurred. There is no direct relationship between road roughness and emissions levels. Models, such as *Mobile 4* and *EMFAC7*, that predict air pollution levels for transportation projects require inputs regarding temperature, travel speed, evaporation rates, and other factors (Lewis et al, 1999), but not pavement quality.

The relationship between fuel consumption and vehicle operating speed is described by the "U-shaped" curves provided in Exhibit VI-14.

Exhibit VI-14
VOC/Uniform Speed Relationship by Type of Vehicle
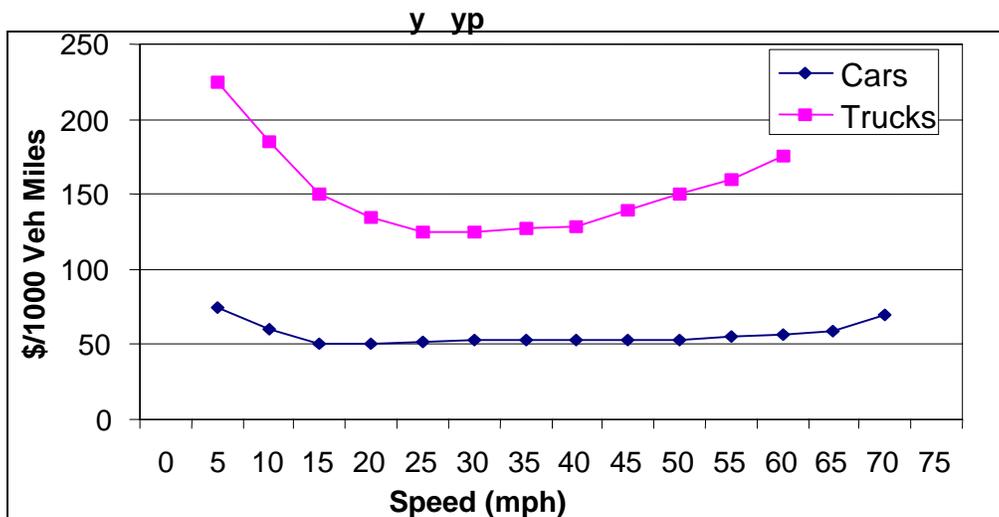
The implication is that many roadway rehabilitation projects that enable motorists' driving speeds to increase beyond the mid-range may also increase vehicle operating costs.

Noise Generation

A significant amount of research has been conducted on the relationship between pavement type and/or road roughness and noise generation. Empirical evidence has shown that increases in road roughness contributes to increased noise levels.

The level of noise over a roadway is determined by vehicle and road interaction – specifically, contact between tires and the road surface. Road/tire noise is affected by a number of factors (in decreasing order of importance):

- Speed
- Road surface type
- Tire type.

Other influences include road surface age, temperature, vehicle underbody and wheel housings, wheel load, tire inflation pressure, and tire size (for trucks).[41]

A study by Von Meier (1995) found that minimization of texture depth at wavelengths of about 10 mm (macrotexture level), and maximization of texture depth at wavelengths of about 2 to 10 mm would reduce tire noise generated by tire vibration for automobiles.

Additional research on noise and pavements has focused on pavement type – concrete, asphalt, slurry, and stone. Yeo and Foley (1997) tested seven different surface types while Dash (1995) tested nine surface types. Both studies found open-graded asphalt, stone mastic asphalt, and slurry seal to be the quietest surfaces.

While the relationship between pavement and noise levels is generally understood, translating noise levels into societal costs based solely on user impacts is problematic. The dollar value of noise generated depends on a variety of factors, many of which are site specific to the project in question, including:

- Noise propagation (how noise travels with respect to distance and physical barriers around the project site)
- Population distribution around project site
- Population characteristics around project site which affects the value (or cost) of noise (varies by income level, land use, and other factors).

Modeling the impact of noise is complex and requires detailed data that would not likely be available for most roadway rehabilitation projects. A potential solution is to equate the user cost associated with reduced noise generation with the cost of

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[41] *McLean and Foley, 1998*

constructing highway sound barriers that produce an equal level of noise reduction. While this approach avoids some of the factors cited above, it raises the issue of whether the construction of a sound barrier is itself a cost-effective solution (i.e., the cost of constructing the sound barrier is less than or equal to the user costs it eliminates). A sound barrier could, in effect, be a costly solution to an in expensive problem. In this case, the cost of constructing a sound barrier would overestimate the user benefits associated with noise reduction.

3.0   METHODOLOGIES IN USE

The next few sections describe how four recently developed, benefit-cost models handle the impact of pavement condition on user benefits:

- Highway Economic Requirements System (HERS)
- RailDEC
- StratBENCOST
- Surface Transportation Efficiency Analysis Model (STEAM).

These are the same four models reviewed in developing the base version of the Cal-B/C model.

3.1   HERS

HERS was developed by the Federal Highway Administration to estimate national benefits associated with varying levels of highway investment, and the national level of funding required to achieve a certain level of system performance. It does not conduct project- or segment-specific analyses.

With the exception of environmental costs (emissions), HERS considers the same user costs as the base version of Cal-B/C, including travel time, vehicle operating costs, and safety (accident) costs. HERS also examines changes in highway operating costs (life-cycle costs) through maintenance cost savings and residual value of the highway improvement.

Certain project components of SHOPP's roadway rehabilitation element are evaluated in HERS, including pavement resurfacing and reconstruction. Although performed on a system-wide basis, the analysis produces a reduction in user costs associated with correcting deficiencies in the pavement condition or with the type of roadway surface.

While the model methodology is not appropriate for incorporation into Cal-B/C, given that it provides a system-wide perspective, the background relationships regarding user costs and pavement conditions could be considered for inclusion in Cal-B/C. Additional research into HERS is being conducted and the applicability of its user-cost/pavement condition relationships will be evaluated.

3.2   RailDEC

RailDEC was developed for the Federal Railroad Administration in order to facilitate investment decisions for rail and rail-related projects. Since the model focuses on rail projects, it does not specifically consider roadway rehabilitation-type projects. While the model does consider changes to highway user operating costs caused by a change in the use of freeway(s) adjacent to new or improved rail projects, it does not consider the effect of pavement quality.

3.3   StratBENCOST

Hickling, Lewis, Brod, Inc. developed StratBENCOST under contract to the Transportation Research Board of the National Research Council. It was designed for rapid analysis and comparison of a number of highway projects, with the objective to allow planners to select the most promising projects for more detailed analysis.

The model has two major sub-parts: a single–segment model and a network model. The first analyzes effects of an improvement project in terms only of traffic on the improved segment. The second allows the comparison of scenarios in a network context, so that the effect of a segment improvement on all traffic on the network can be captured. It is the first sub-part that is comparable in function to Cal-B/C.

StratBENCOST analyzes changes in four cost categories:

- Travel time costs
- Vehicle operating costs
- Accident costs
- Emissions costs.

A variety of project types can be analyzed using StratBENCOST including those most relevant to this discussion – rehabilitation and resurfacing, asphalt vs. concrete, and partial vs. full resurfacing. Changes in user costs associated with roadway rehabilitation projects are measured by changes to the pavement serviceability index (PSI).[42] StratBENCOST applies adjustment factors based on research conducted by the Texas Transportation Institute[43] applied to vehicle operating costs when the PSI of a roadway is affected.

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[42] *Road profiles measure the accumulated pavement suspension deflections over a length of roadway, and are measured in inches/mile or m/km – like the IRI (Hegmon, 1993). From these statistics, the PSI is measured. PSI is the roughness determined by correlation from multiple measurements. The PSI is measured on a scale of 1 to 5 (5 reflecting a perfectly smooth surface). The PSI is an estimate, based on the actual road profile, of the pavement serviceability rating which is a subjective rating of pavement roughness also based on a scale of 1 to 5. PSR can be converted into units of IRI using the following formula: PSR=5/exp(C*IRI), where C equals .226 for flexible pavements and .286 for rigid and composite pavements, and IRI is measured in m/km (Hegmon, 1993).*

[43] *"Technical Memorandum for National Cooperative Highway Research Program (NCHRP) Project 7-12." Texas Transportation Institute, The Texas A&M University System, College Station, Texas, January 1990.*

While vehicle operating costs are calculated according to speed and roadway geometry and adjusted according to pavement condition, speed is not affected by pavement condition but only according to roadway capacity and geometry factors. Also of interest is that the research upon which the model's vehicle operating cost lookup tables are based found no relationship between fuel consumption and roadway surface condition (see section 3.1).

3.4   STEAM

STEAM was developed by the Federal Highway Administration to allow for detailed comparison of proposed transportation projects in corridor and system-wide analysis. The model estimates the impacts of transportation investments and policies, including major capital projects, pricing, and travel demand management.

In addition to the user costs included in the models already discussed, STEAM also considers the following effects:

- Consumer surplus from new travel
- Noise
- Changes in public agency revenues, such as fares, tolls and taxes.

The last of these effects is frequently considered a transfer payment and not included in benefit-cost models. The inputs to the STEAM software are from the user's four-step planning model:

- Person trip tables for passenger travel and vehicle trip tables for truck travel
- Travel time and cost matrices for transit networks
- Highway network output from traffic assignment.

The STEAM model uses the trip tables, travel time and cost matrices, and traffic volume inputs directly and does not adjust for any pavement condition effects. As a result these effects must be calculated outside of the model and the input data adjusted in order for pavement rehabilitation projects to be modeled.

4.0   CALTRANS METHODOLOGY

Most of the input data required to analyze the changes in user costs associated with roadway projects are already collected and stored in the Caltrans Pavement Management System (PMS). Since the PMS is an important source of input data for analyzing pavement rehabilitation projects in Cal-B/C, it is described first, followed by the way that Cal-B/C handles pavement rehabilitation projects.

4.1 PAVEMENT MANAGEMENT SYSTEM

The Caltrans Pavement Management System (PMS) in use at the time of the interim update to the Cal-B/C model (2000) was developed in the late 1970s to provide a structured, engineering approach to managing pavements. It is the primary tool for cataloging pavement conditions, determining where repairs are needed, prioritizing projects, and estimating fiscal needs for system repair.

Caltrans uses a three-criteria approach for determining the pavement rehabilitation needs of its roadways. These criteria are:

- Maintenance Service Level
- Distress Level
- Ride Quality.

The maintenance service level (rated as MSL1, MSL02, or MSL3) is determined by roadway type (e.g. freeway or expressway) and/or traffic volume. Interstate highways receive the highest designation (MSL1) while low volume routes are categorized as MSL3.

The other two criteria reflect the condition of the pavement. Information about pavement condition on the state's highway system for inclusion in PMS is collected annually through a Pavement Condition Survey. Pavement is rated based on structural and functional (ride quality) characteristics. A pavement's structural condition is evaluated based on distress types that are unique by pavement type (flexible or rigid pavements). Caltrans classifies distress level into three categories – none, minor, or major.

The functional characteristics of pavement segments are measured through road profiles, and expressed in terms of IRI (measure described in Section 3) in inches/meter. IRI is then translated into either an acceptable or unacceptable ride. Based on the combination of the three criteria – maintenance service level, distress, and ride quality – a roadway segment is assigned a priority value ranging from 1 to 14. Roadways with priority values 1 through 6 are considered to be in immediate need of rehabilitation.

Caltrans has adopted a new roadway rehabilitation strategy, which represents a significant change from previous practice. The previous prioritization system (just described) reflects a "worst first" approach to pavement rehabilitation, with the roadways most in need of repair being given the highest priority values. Caltrans is shifting to a "preventive" approach, which calls for the highest priority to be given to the most cost-effective strategies. This approach minimizes long-term agency costs as shown in Exhibit VI-15.

Exhibit VI-15
Pavement Condition Versus Costs Of Repair
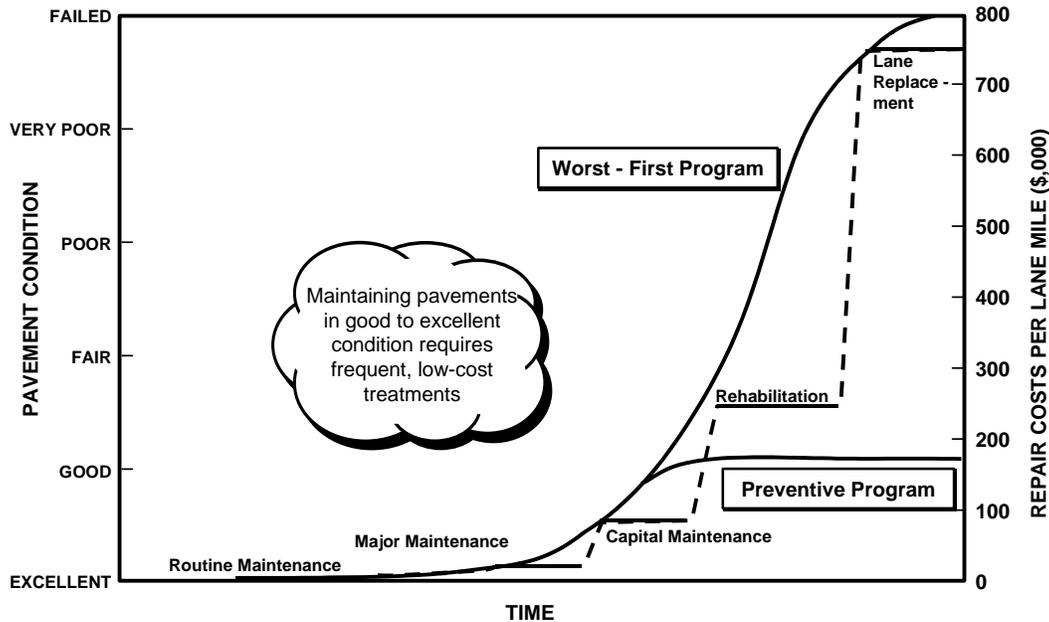
Source: Ten-Year Highway System Rehabilitation Plan

This approach required a new PMS. Caltrans recently developed an Advanced Pavement Management System (APMS), which replaced the prior PMS. The APMS prioritizes projects using benefit/cost analysis (incorporated directly into the system) rather than the previous three-tier approach. The APMS benefit/cost analysis is expected to consider some user costs as well as agency construction costs over a 35-year life cycle. The PMS, and ultimately the APMS, can serve as the data source for pavement conditions, as measured by IRI, for analysis of roadway rehabilitation projects in the updated Cal-B/C model.

4.2 CAL-B/C AND PAVEMENT REHABILITATION PROJECTS

Incorporating the evaluation of pavement rehabilitation projects required the following changes to Cal-B/C:

- *The addition of a rule-of-thumb deterioration curves for pavement.* Roadway pavement deteriorates under both the build and the no-build scenarios. The deterioration curves describe the likely state of the pavement in Year 20 under different vehicle loadings. It is expected that model users input future road roughness information. However, the deterioration curves are available if this information is not known.

- *An adjustment to the speed calculation module that takes into account changes in pavement condition due to pavement rehabilitation projects.* Rougher

pavement generally results in lower vehicle operating speeds. A look-up table adjusts the speed predicted in the Cal-B/C speed calculation module on the basis of pavement conditions. This adjustment occurs only for pavement rehabilitation projects.

- *An adjustment to the fuel consumption look-up in the calculation of vehicle operating costs.* Rougher pavement leads to greater friction and fuel consumption. The Cal-B/C fuel consumption table already considers speed. For pavement rehabilitation projects only, the results of the fuel consumption table are adjusted on the basis of road roughness.

- *A modification to non-fuel costs for roadway rehabilitation projects based upon changes in road roughness.* Although the research shows a fairly wide range of estimates, rougher pavement generally results in greater vehicle wear and tear and higher maintenance costs. A lookup table based upon road roughness is used to adjust non-fuel costs for pavement projects only.

These changes capture the effect of pavement condition on travel times, vehicle operation costs, and emissions for pavement projects. The effect of pavement condition on accident costs depends on local weather conditions, but is fairly slight and not included in Cal-B/C.

To analyze pavement rehabilitation projects, users begin by selecting the project type as a pavement project. This project type cannot be selected with other highway projects, which are new project types rather than improvements to existing infrastructure.

Cal-B/C captures the user benefits associated with a pavement improvement using pavement roughness as measured by IRI. The build case of rehabilitating the pavement is compared against the no-build case of not improving the pavement. In order to project potential user benefits, the user costs of the two scenarios are compared, assuming that no other improvements are made (including routine maintenance). Since pavement is generally maintained in California, the model compares scenarios with pavement quality well outside the range typically experienced.

Users are asked to provide an IRI value for Year 1 and Year 20, both with and without the rehabilitation project. If users do not know the expected IRI in Year 20, the model will calculate the value. Cal-B/C calculates the Year 20 IRI using decay relationships developed by Paterson for the World Bank (1987). The rate of decay varies by traffic loads – light, medium, or heavy - over the roadway segment in question. The pavement decay rates incorporate wear caused by potholes, cracking and patching, deformation, the environment, and age. IRI values for each year over the twenty year project life are interpolated using the Year 1 and Year 20 IRI values. These decay rates represent "rules of thumb" and should be replaced by area-specific data, if available.

User costs calculated in previous versions of Cal-B/C did not take pavement condition into account. In order for user costs to be calculated for pavement rehabilitation projects in this update of Cal-B/C, the user cost calculations had to be adjusted for variable pavement conditions. Since information on the average IRI for the entire State Highway System is not available, the user cost calculations are calibrated at a value of 175 inches/mile. This corresponds to the point at which pavement roughness progresses from fair to poor and user costs increase. Using a higher IRI calibration results in a conservative estimate of user benefits for pavement projects.

Cal-B/C considers three effects of pavement condition related to user costs:

- Relationship between pavement quality and speed
- Relationship between pavement quality and fuel consumption
- Relationship between pavement quality and non-fuel costs.

To capture the influence of pavement quality on vehicle operating speeds, Cal-B/C adjusts the speeds that are calculated in the model (based upon volumes using the standard capacity constraint function found in regional demand models)[44] and assumed to occur at an IRI of 175 inches/mile. The speed adjustments are based upon the theoretical work by McLean and Foley (1998). This is the most recent research available and provides separate tables for cars and trucks. Although the McLean and Foley tables are based on more recent, fuel efficient vehicles, they show patterns similar to older data included in the Federal Highway Performance Monitoring System (HPMS).

Separate adjustment factors are applied for cars and trucks, which are presented in Exhibit VI-16 below. For cars, speeds remain unchanged from existing Cal-B/C calculations for IRI values up to 250 inches/mile, while truck speeds are increased over existing model calculations for IRI values of 150 inches/mile and less.

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[44] *For more information on how Cal-B/C estimates vehicle operating speeds from traffic volumes see the Cal-B/C Technical Supplement section on peak period effects.*

Exhibit VI-16
Factors Used to Adjust Vehicle Operating Speeds for Pavement Condition

0	1.00	1.02
25	1.00	1.02
50	1.00	1.02
75	1.00	1.02
100	1.00	1.02
125	1.00	1.02
150	1.00	1.01
175	1.00	1.00
200	1.00	0.98
225	1.00	0.95
250	1.00	0.92
275	0.99	0.89
300	0.98	0.86
325	0.97	0.83
350	0.96	0.81
375	0.95	0.78
400	0.94	0.76
425	0.93	0.73
450	0.92	0.71

Note: The speed initially calculated in Cal-B/C is multiplied by the percentage given above to take into account pavement condition.

Cal-B/C uses similar factors to adjust the fuel consumption calculation for pavement rehabilitation projects. Fuel consumption is initially calculated using the standard tables in Cal-B/C in Year 1 and Year 20, both with and without the project. These values are adjusted by the factors provided in Exhibit VI-17.

Exhibit VI-17
Factors Used to Adjust Fuel Consumption for Pavement Condition

		Truck
0	0.97	0.96
25	0.98	0.97
50	0.98	0.97
75	0.98	0.98
100	0.98	0.98
125	0.99	0.99
150	1.00	0.99
175	1.00	1.00
200	1.01	1.01
225	1.01	1.02
250	1.02	1.03
275	1.03	1.04
300	1.03	1.05
325	1.04	10.6
350	1.05	1.07
375	1.06	1.08
400	1.07	1.10
425	1.08	1.11
450	1.09	1.13

Note: The fuel consumption initially calculated in Cal-B/C is multiplied by the percentage given above to take into account pavement condition.

The fuel adjustment factors are based upon the Texas Transportation Institute research (Southwest Region University Transportation Center, Updated Fuel Consumption Estimates for Benefit-Cost Analysis of Transportation Alternatives) for vehicles operating at 35 MPH and 65 MPH. These speeds were chosen to capture the variety of traffic conditions that exist on California freeways and expressways. The adjustments for the two speeds are similar and are averaged to create factors used in Cal-B/C. These are presented in Exhibit VI-17.

Finally, non-fuel operating costs are adjusted for pavement conditions based on the ARRB Research Board's TR VOC Model as reported in McLean and Foley (1998). As shown in Exhibit VI-18, non-fuel costs are not modified for IRI values of up to 125 inches/mile for both cars and trucks. Non-fuel operating costs are calibrated to 125 inches/mile, since the TR VOC suggests that this is the point at which non-fuel costs begin to increase above the average for excellent and good pavement.

Exhibit VI-18
Factors Used to Adjust Non-Fuel Costs for Pavement Condition

		Truck
0	1.00	1.00
25	1.00	1.00
50	1.00	1.00
75	1.00	1.00
100	1.00	1.00
125	1.00	1.00
150	1.02	1.02
175	1.03	1.04
200	1.05	1.06
225	1.07	1.08
250	1.09	1.10
275	1.11	1.12
300	1.12	1.14
325	1.14	1.16
350	1.16	1.18
375	1.18	1.20
400	1.19	1.22
425	1.21	1.24
450	1.23	1.26

Note: The non-fuel costs initially calculated in Cal-B/C is multiplied by the percentage given above to take into account pavement condition.

VII. REFERENCES

VII.   REFERENCES

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