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INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Evaluation of Traffic Simulation Model Use in the Development of Corridor System Management Plans (CSMPs)

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California PATH Research Report
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16. ABSTRACT

Following passage of the Highway Safety, Traffic Reduction, Air Quality, and Port Security Bond Act, Caltrans has required that freeway corridors within California have a Corridor System Management Plan (CSMP) in place for these corridors to receive state funding. CSMPs are planning documents that examine the mobility, reliability and safety of transportation corridors based on a comprehensive performance assessment. CSMPs first seek to determine how a corridor is performing, and why it is performing that way. Based on the results of the comprehensive analyses, strategies and improvements that can best address the identified problems are then evaluated and prioritized.

The above requirements have resulted in the development of CSMPs for 45 major freeway corridors across California. For 31 of these corridors, large traffic simulation models, based on microscopic, macroscopic, and hybrid microscopic/mesoscopic approaches, were developed to assess the impacts of proposed strategies on corridor performance. The goal of this project was to evaluate the effectiveness and value of using traffic simulation in the development of CSMPs, and more specifically to determine whether the use of simulation models provided benefits that exceeded their actual and apparent costs. Specific activities that were conducted towards this end include a review of traffic simulation capabilities, an assessment of experiences with traffic simulation for corridor evaluations through a survey of simulation modelers and decision-makers, a detailed review of simulation modeling efforts and utilization of their results for six CSMP corridors, a review of cost and time expenditure for the development and utilization of simulation models for 18 CSMP corridors, a review of simulation modeling efforts in support of the USDOT's Integrated Corridor Management (ICM) program, the identification of gaps and critical issues associated with the utilization of traffic simulation in corridor operational evaluations, the identification of lessons learned regarding the use of traffic simulation models, and the presentation of recommendations for improving the utilization of traffic simulation models in future CSMP operational evaluations.

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EXECUTIVE SUMMARY

Following the passage of the *Highway Safety, Traffic Reduction, Air Quality, and Port Security Bond Act* in November 2006, the California Transportation Commission (CTC) has required that all major transportation corridors within the state have a Corridor System Management Plan (CSMP) in place for its governing agency to receive funds from the $4.5 billion Corridor Mobility Improvement Account (CMIA) or $1 billion Highway 99 Bond Program. For each corridor, CSMPs are to determine how it is performing, why it is performing that way, and to propose improvement strategies that can best address the identified problems while maximizing the use of taxpayer dollars. Ultimately, CSMPs are to serve as a tool that all stakeholders in the operation of a corridor can use for cooperatively managing it and efficiently optimizing its safety, mobility, productivity and reliability.

CSMPs generally seek to improve corridor performance by assessing the potential benefits of candidate capital infrastructure projects, operational changes, and system management strategies. They are different from traditional traffic management strategies in that they seek to manage the various components of a transportation corridor as a system rather than as independent elements. In this context, they subscribe to Caltrans' system management approach. While a freeway is generally the focus of the evaluations, analyses also often consider the performance of parallel arterials and nearby roads. CSMPs are also meant to approach corridor problems from a multi-modal standpoint. This means considering the needs of transit agencies, intercity and regional rail services, commercial fleets, as well as pedestrians and cyclists where relevant, in addition to the needs of passenger cars.

To address the complexity of the required operational evaluations, traffic simulators have been used for 31 of the 45 corridors for which a CSMP has been completed since 2006 to help assess the benefits of proposed improvement strategies. These evaluations have resulted in the development of 9 macroscopic, 26 microscopic models, and 1 hybrid mesoscopic/microscopic model of freeway corridors often extending over 30 miles in length and including in many cases a partial or complete modeling of parallel arterials. More than 31 models were developed, as some corridors were split into separate sections to enable the development of more manageable models. Across all corridors, Caltrans District staff directly performed the modeling for three corridors. Eight contracted private consulting firms conducted the simulation evaluations for the remaining 28 corridors. In some cases, the firm leading the CSMP development also conducted the modeling, while in others a firm specializing in traffic simulation modeling was instead subcontracted by the CSMP lead agency.

While significant resources have been expended on the development of simulation models, the benefits that were obtained from their use have generally been found to outweigh their development costs. A majority of modelers, project managers and decision-makers have, for instance, indicated that the models that were developed have generally met the initial expectations that were placed on them and fulfilled their intended role. Although some of the modeling efforts required more time than expected, many of the problems can be associated with the novelty of the evaluation effort, which was a first attempt nationwide at evaluating a large set of often complex freeway corridors using microscopic traffic simulators. It is thus anticipated that the lessons that were learned from the CSMP modeling efforts will enable future evaluations to be completed in shorter time and with fewer resources. Potential evidence of this trend can be found in the recent completion of the CSMP for the I-5 corridor in Orange County in slightly less than 12 months, as opposed to an average of 34 months for earlier efforts, and for an overall lower cost.

The following are specific positive experiences that are associated with the use of simulation models to support the CSMP evaluations:

- The simulation models helped in factoring into the evaluations the complex interactions that often exist between road geometry, driver behavior, traffic control devices, and traffic management strategies. Such interactions are often difficult to fully consider when using other analytical tools, such as the Highway Capacity Manual.
- Within many corridors, simulation evaluations have been influential in affecting investment decisions, enabling decision-makers to justify previous decisions, delay or remove projects having a low return on investment, and prioritize project implementation schedules.
- In many cases, visual animations have been instrumental in helping decision-makers to understand the operational problems of a corridor and to better assess the benefits associated with specific sets of improvements.
- While challenges were sometimes encountered in explaining to decision-makers or project managers why simulation results differed from initial expectations, the dialogue that developed around these challenges often led to an understanding of the desirability of specific improvements or the identification of new potential improvements. The discussions also led on occasion to the establishment of improved decision-making partnerships among stakeholders.
- The modeling efforts provided an environment in which professionals from various areas worked closely and exchanged information. This facilitated the building of knowledge, technical and managerial skills, and professional expertise regarding the use of simulation.
- Upon completion of its last remaining modeling effort, Caltrans District 12 will be the first District to have simulation models covering all major regional freeway corridors.

The ability to use the simulation models that were developed for the CSMP corridors to support non-CSMP evaluations is another important potential benefit. The availability of calibrated models covering key urban freeway corridors can entice Caltrans staff to consider using simulation instead of analytical methods to evaluate proposed transportation projects. While adjustments may still need to be made to the available models, these modifications should carry a much lower cost than developing a new model from scratch. Adjustments made during repeated model uses may further allow a model to be periodically updated to current conditions, and thus to remain in or close to a ready-for-use state.

Based on the various demonstrated benefits and positive experiences, it is strongly recommended that traffic simulation tools, whether microscopic or macroscopic in nature, continue to be used to support CSMP operational evaluations. This recommendation is supported by the fact that leadership from many Caltrans Districts, as well as various partner agencies, expressed a desire to continue using simulation as a key tool for corridor operational evaluations. While a preference is often placed on using microscopic models, due to their ability to model in great detail the behavior of individual vehicles, macroscopic models can still be used to reduce the cost and time needed to complete an analysis where the use of such models is found to be adequate. However, despite their promising concept, there is not yet enough evidence to provide a specific recommendation regarding the use of hybrid microscopic/mesoscopic models.

ANALYSIS OF SIMULATION STUDY COST AND DURATION

A review of contractual documents indicated that CSMP simulation studies typically took between 24 and 42 months to complete, with an average of slightly over 34 months and extremes of 12 months and 55 months. An analysis of expenditures further revealed the following:

- Overall CSMP costs ranged from $550,000 to $1.50 million, with an average of $970,000.
- An average of slightly above $76,000 was spent on data collection contracts (excluding data processing), with extremes of $10,000 and $209,000.
- An average of $24,000 was spent on peer-reviews, with extremes of $14,400 and $28,900.
- An average of $871,900 was spent on the coding, calibrating and use of simulation models, with extremes of $503,800 and $1.29 million.
- On a per mile basis, the average evaluation cost is $32,700, with extremes of $12,600 and $67,200. On a per interchange basis, the average is $35,400, with extremes of $10,700 and $71,200.

The longest or costliest evaluations were not necessarily those featuring the lengthiest corridors or more complex freeways. Several factors that have affected time and cost requirements include:

- Differences in geographical scope, such as length of the modeled freeway and extent of modeling of surrounding arterials.
- Differences in road network complexity, such as the number of simple and complex interchanges, the presence of HOV lanes, ramp meters, or other intelligent applications.
- Availability of a previously developed model that could be used as a starting modeling point.
- Differences in available data and data quality.
- Number of bottlenecks and complex merging/weaving sections to model.
- Expertise of the modeling team in handling complex modeling and calibration issues.
- Number and complexity of the scenarios to be evaluated (number and type of improvements, extent of modifications to the road network, need to develop custom plug-in modules, etc.).
- Expertise of the District review team in not accepting poor modeling work.

The observed variability in project duration and expenditures made it particularly difficult to develop an average that could be applied to all CSMP corridors. As a result, average costs can only be used as preliminary estimates for early project planning purposes.

CRITICAL ISSUES WITH THE USE OF SIMULATION MODELS

In order to assess gaps in current practices and areas of potential improvements, the two following activities were conducted as part of the evaluation projects:

- **Review of simulation modeling practices associated with six CSMP corridors** – Simulation practices were reviewed for the I-80 and US-101 corridors in District 4, the I-5 corridor in District 7, the I-205/I-5 corridor in District 10, the I-805 corridor in District 11, and the I-405/SR-22 corridor in District 12. These reviews covered models that have been developed using Paramics, VISSIM, CORSIM, TransModeler and FREQ 12.

- **Survey of simulation modelers, project managers and decision-makers** – This survey collected simulation experiences from 21 Caltrans employees, 3 individuals from MPOs within California, 10 California-based consultants, and one out-of-state consultant. Sixteen of these respondents acted as modelers, 17 as project managers and 6 as decision-makers, with some having dual duties. The responses provided by 33 of the 35 respondents further covered experiences pertaining to the development of 15 of the 31 simulation-based CSMPs.

The following outlines the various elements that were found important to consider when using simulation models to conduct operational evaluations:

- Incorrect perceptions regarding the modeling capabilities of commercial simulation models.
- Correct understanding of the relative benefits of various modeling approaches.
- Impacts of data availability and quality on modeling results.
- Ability to develop adequate origin-destination (O-D) flow patterns from regional travel demand models or from traffic count data using O-D matrix estimation (ODME) methods.
- Ability to model and simulate large road networks with reasonable speed.
- Ability to model desired improvements with built-in functions or custom plug-in modules.
- Ability of agency staff to use or learn commercially available simulation models.
- Impacts of time and budget constraints on modeling and evaluation activities.
- Application of consistent and relevant calibration standards.
- Consistent and coherent model review process supported by individuals having adequate knowledge of the simulation models being used and relevant traffic operations principles.
- Development of coherent strategies for bundling improvement projects.
- Adequate application of simulation models to conduct evaluations, particularly regarding the number of runs required to adequately account for variability across individual runs.
- Use of performance measures suitably linked to corridor improvement objectives.
- Consistent methods for assessing the operational performance of corridors.
- Adequate documentation of modeling, review, and evaluation activities.
- Maintenance of developed simulation models following the completion of an evaluation.

RECOMMENDATIONS FOR IMPROVING THE USE OF SIMULATION IN CSMP EVALUATIONS

The following are key recommendations that were identified to improve development and use of traffic simulation models in future corridor operational evaluations:

- Project managers and decision-makers should be adequately informed of the needs, limitations and risks associated with using simulation to evaluate long or complex corridors.

- While microscopic models are often perceived as ideal evaluation tools, there are situations in which a simplified modeling approach is better suited. A needs analysis should be conducted to determine which model is best suited for a specific project.

- A clear modeling scope should be defined for each simulation project prior to initiating the modeling. This includes defining the extent of the network to model, the time periods to consider, the rules for dividing large networks into smaller sections, the evaluation horizon(s) to consider, and a general concept for the development of scenarios.

- A detailed data collection plan indicating what is to be collected, from which sources, in which quantity and for what purpose, as well as how the validity of data will be assessed, should be developed by the modeling team and submitted for approval by Caltrans prior to initiating the model development. The plan should not only cover efforts listed in the task order but also any additional efforts deemed necessary to support the proposed evaluations.

- Wherever travel demand models are used as information sources, active participation should be sought from individuals responsible for the development and/or use of these models.
- Current calibration standards should be reviewed to address gaps regarding the modeling of bottlenecks, HOV/HOT lanes, arterial intersections, route selection, and transit elements.
- To ensure consistency, a uniform review process should be applied across all Districts. In this process, peer-reviewers should have or be given an adequate knowledge of the simulation models being used, as well as given more than two weeks to conduct a review. The rationale for all model approvals and rejections should further be documented in writing.
- Reviewed models exhibiting a high number of simple mistakes should be returned to their modeling team for revisions before continuing with the review. Scenario evaluation should also not be allowed to start until a calibrated model has been officially approved.
- Guidelines should be developed to determine when it may be in the best interest of Caltrans to terminate a modeling project facing continuous difficulties.
- A consistent standard should be developed for determining the number of simulation runs to execute, requiring, for instance, all modeling teams to justify their choices. Ideally, the number of runs should be based on the variability of simulation outputs. Assessments based on a single run should not be allowed for any stochastic simulation model.
- All performance measures should be determined and agreed upon by all project stakeholders, and linked to specific corridor management objectives.
- Corridor segmentation should ideally be based on major bottlenecks and key interchanges, and should result in segments that are ideally at least 2 miles in length.
- A formal cost/benefit analysis, using Cal B/C or other accepted model and presenting results in a graphical format, should be conducted for all CSMPs.
- Document templates should be developed to standardize project reporting.
- Caltrans should explore the possibility of maintaining in-house a core group of individuals with adequate simulation expertise who can be called upon to support or supervise modeling activities conducted by District staff or external consultants. In-house staff may include individuals based at Caltrans Headquarters in Sacramento and individuals with knowledge of local networks strategically based in key Caltrans Districts.

Implementation of the above recommendations should provide a path to strengthen how traffic simulation models are used to evaluate corridor operations by promoting standardized, transparent and accountable practices.

It is further recommended that a program supporting the development and maintenance of simulation models should be implemented within individual Districts. Current practice within some Districts can be used as a starting point. The program should identify which Division would be responsible for storing the model files, the supporting data, and the modeling reports; how frequently a model should be updated when not actively used; and who would be responsible for updating the model. To accomplish such a goal, Caltrans will need to develop a formal policy regarding the use of simulation to support both CSMP and non-CSMP evaluations, and to identify appropriate funding mechanisms to support the modeling effort, particularly for simulation projects that are anticipated to last more than one year, due to the need to appropriate funds over multiple fiscal years.

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1. INTRODUCTION

In 2003, the California Department of Transportation (Caltrans) embarked upon a process to demonstrate and assess the viability of developing Corridor System Management Plans (CSMPs) for major freeway corridors across the state, particularly those experiencing congestion. For each corridor, the primary intents of developing a CSMP were to:

- Determine how a corridor is performing;
- Identify why the corridor is performing that way; and
- Propose strategies and improvements that can best address the identified problems.

CSMPs are different from traditional traffic management strategies in that they seek to manage the various components within a transportation corridor as a system rather than as independent elements. While a freeway is typically the focus of the evaluations, analyses also often consider the performance of parallel arterials and nearby roads. A few of the evaluations considered the needs of other relevant travel modes, such as passenger cars, urban transit services, intercity and regional rail services, and commercial vehicles. While current CSMPs did not consider the needs of cyclists or pedestrians, these elements may be considered in future evaluations if they are deemed relevant to achieve multi-modal operational objectives. Within each corridor, the goal was to select improvement strategies yielding high benefit-cost ratios and maximizing the use of taxpayer dollars. The improvement strategies considered ranged from short-term operational improvements to long-term capital projects and often included the use of Intelligent Transportation Systems (ITS) technologies. System or demand management improvements were also considered in some cases.

While CSMPs are viewed as key tools for managing transportation corridors, the development of comprehensive and high quality plans is a complex and costly proposition. To comprehensively evaluate the effectiveness of corridor improvement strategies, complex traffic impacts studies are required. To support such studies, many CSMPs have relied on traffic simulators to produce quantitative assessments of the potential impacts of proposed improvements on traffic behavior and corridor operations. Data provided by simulation models also helped decision-makers to compare the anticipated impacts of individual or groups of strategies and to develop effective corridor improvement and management strategies.

Although simulation models can be valuable evaluation tools, the development of well-calibrated models for corridors covering 20 to 40 miles of freeway can be a time-consuming and costly endeavor. Simulation models often require significant data to be collected to characterize traffic movements along a corridor. In addition to the data needs, there is the challenge of calibrating the various model parameters to ensure that real-world traffic behavior is adequately replicated. These demands and challenges can result in perceived high development and calibration costs that may lead to question the value and cost-effectiveness of using traffic simulation models to assess corridor performance.

The goal of this project was to evaluate the role and effectiveness of traffic simulation studies in the development of CSMPs. A more specific aim was to understand whether the use of simulation added net value to the projects, i.e., provided benefits that exceeded the model development and utilization costs. More specific questions that this project sought to answer include:

- What management strategies could be modeled?
- Could the simulation model adequately replicate the strategies considered?

- Was there adequate and sufficient data available to model various corridor elements?
- Is the current processing for developing, reviewing and using simulation models adequate?
- How simulation models were used to evaluate candidate improvements?
- How simulation data affected the selection and prioritization of improvements?
- Was the use of traffic simulation models justified?
- What recommendations could improve the utilization of simulation models in CSMPs?

Answers to the above questions were developed through a detailed review of simulation modeling activities in six recently completed CSMP studies, as well as a general review of how simulation has been used in other CSMP projects. A survey of simulation modelers, model users, project managers and decision-makers was also conducted to collect the views and experiences of transportation professionals regarding the use of simulation to support corridor operational evaluations.

The remainder of this report is organized as follows:

- **Section 2** presents an overview of CSMP development activities in California.
- **Section 3** presents an overview of traffic simulation modeling principles and capabilities offered by state-of-the-art commercial simulation tools.
- **Section 4** presents the key findings of a survey of professionals involved in the development and use of traffic simulation models for corridor operational evaluations.
- **Section 5** presents a detailed review of the traffic simulation modeling efforts associated with six CSMP corridors across five Caltrans Districts.
- **Section 6** presents a brief analysis of the time that has been expended and costs that have been incurred for the development of traffic simulation models for 18 CSMP corridors.
- **Section 7** analyzes the use of traffic simulation within the USDOT's Integrated Corridor Management (ICM) Program, which mirrors in many aspects the CSMP operational improvement objectives.
- **Section 8** details gaps that have been identified within the CSMP simulation development process, and various critical issues that must be considered when using simulation models for corridor evaluations.
- **Section 9** presents lessons learned that were identified through the current project.
- **Section 10** presents specific recommendations for the development, utilization, and maintenance of traffic simulation models in future CSMP operational evaluations.
- **Section 11** finally presents general conclusions regarding the use of traffic simulation to support corridor evaluations and the eventual development of implementation plans for corridor improvements.

2. OVERVIEW OF CORRIDOR SYSTEM MANAGEMENT PLANS

Following passage of the *Highway Safety, Traffic Reduction, Air Quality, and Port Security Bond Act* in November 2006, the California Transportation Commission (CTC) has indicated that it would give priority funding to projects for which a Corridor System Management Plan (CSMP) has been adopted or was under development. This requirement was applied to all projects that received funding from the $4.5 billion Corridor Mobility Improvement Account (CMIA) or $1 billion Highway 99 Bond Program (see General Program Policy #7, *Corridor Mobility Improvement Account Program Guidelines*, adopted November 8, 2006).

The above requirement resulted in the development of a CSMP for 45 freeway corridors across California. To help understand the purpose of CSMPs, how they are developed, and the importance that traffic simulation played in their development, the following elements are described in the subsections that follow:

- Purpose of CSMPs;
- Operational objectives;
- List of corridors for which a CSMP has been developed;
- CSMP corridors with a simulation evaluation component;
- CSMP development process;
- Transportation system improvements considered; and
- Performance measures considered.

2.1. PURPOSE OF CSMPS

The goal of a Corridor System Management Plan (CSMP) is to define how a travel corridor is performing, understand why it is performing that way, and recommend system management strategies to address the identified problems within the context of a long-range planning vision. Ultimately, CSMPs are to serve as a tool that all stakeholders in the operation of a corridor can use for cooperatively managing it and efficiently optimizing its safety, mobility, productivity and reliability. CSMPs also meant to be approach corridor problems from a multi-modal standpoint. This means considering the needs of transit agencies, intercity and regional rail services, commercial fleets, as well as pedestrians and cyclists where relevant, in addition to those of passenger cars.

As illustrated in Figure 1, CSMPs are guided by Caltrans' system management approach. This approach, represented by the triangle diagram at the bottom of the figure, seeks to manage transportation systems through:

- Comprehensive system monitoring and evaluation;
- Adequate maintenance and preservation;
- Coordinated land use and demand management approaches;
- Applications of Intelligent Transportation System (ITS) technologies, particularly advanced traffic management strategies and enhanced traveler information systems;
- Implementation of targeted operational improvements; and
- Improvements in system prevention and safety.

Contrary to traditional management approaches, CSMPs seeks to manage the various components of a transportation corridor as a system rather than individual units. This is in recognition of the fact that the efficient management of a transportation system is contingent on all of its components working together. Improvement strategies are therefore developed not only to resolve specific problems, but to optimize as a whole the transport of persons and goods along a corridor. Improvement strategies thus do not only seek to maximize the efficiency and productivity of a transportation system, but also the cost effectiveness of new investments.

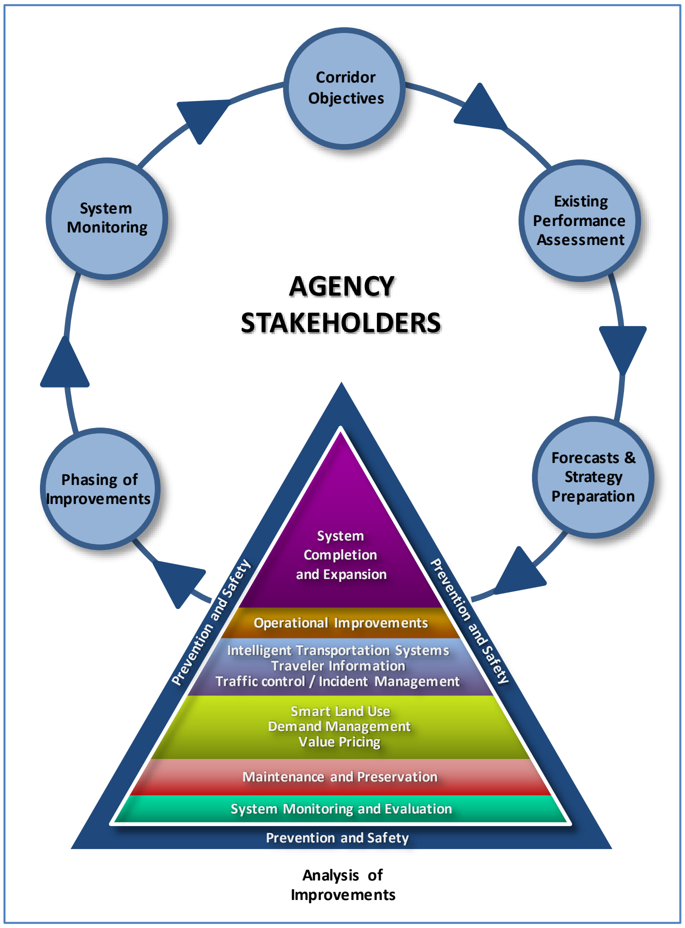

Figure 1 – Caltrans Transportation System Management Approach
(Adapted from SANDAG's I-15 CSMP Documents)

2.2. OPERATIONAL OBJECTIVES

As indicated, CSMPs are developed with the primary goal of improving the overall operation of transportation corridors. Depending on the specific needs of each corridor, this general goal is achieved by considering one or more of the following targeted operational objectives:

- Reducing delay within a corridor (increasing mobility);
- Reducing variations in travel time (improving reliability);
- Reducing accidents and injury rates (improving safety);
- Restoring lost lane miles (improving productivity); and
- Reducing distressed lane miles (improving system preservation).

2.3. CSMP CORRIDORS

Table 1 lists the transportation corridors for which a CSMP has been completed as of June 2012. The list includes 45 corridors spread across 10 Caltrans Districts and includes all major freeway corridors across the state. Most of the CSMPs that have been produced are considered as first-generation documents, i.e., documents meant to be periodically updated as the agencies responsible for the management of each corridor go through new evaluation and planning cycles.

Table 1 – CSMP Transportation Corridors

Corridor	CSMP Completion Date	Corridor	CSMP Completion Date
District 2 – Redding		**District 3 – Marysville**	
I-5	June 2008	I-80	May 2009
SR-99	July 2009	US-50	May 2009
		SR-32	April 2011
		SR-49	May 2009
		SR-65	May 2009
		SR-99 (Chico)	May 2009
		SR-99 & I-5	May 2009
District 4 – San Francisco Bay Area		**District 5 – San Luis Obispo**	
I-580/I-238	May 2010	US-101 Santa Barbara	Nov. 2010
I-880	Oct. 2010	SR-1/SR-183	Oct. 2011
I-80 East	Oct. 2010	SR-46	June 2009
I-80 West	Sept. 2010		
US-101 Marin	Feb. 2011		
District 6 – Fresno / Tulare		**District 7 – Los Angeles / Ventura**	
SR-46	Oct. 2008	I-5 North	Sept. 2010
SR-58	Sept. 2011	I-5 South	Sept. 2010
SR-99 (Urban)	April 2009	I-210	Sept. 2010
SR-99 (Rural)	Nov. 2008	I-405	Sept. 2010
SR-198	Oct. 2008	US-101 Ventura	Nov. 2010
District 8 – Riverside / San Bernardino		**District 10 – Stockton**	
I-10	June 2011	I-205/I-5	May 2010
I-15	Oct. 2011	SR-4	Oct. 2008
I-215	July 2011	SR-99 San Joaquin County	Sept. 2008
SR-91	July 2011	SR-99 Merced	Oct. 2008
		SR-99 Stanislaus	April 2011
		SR-108	Sept. 2008
		SR-219	Sept. 2008
District 11 – San Diego / Imperial County		**District 12 – Orange County**	
I-5 North Coast	Aug. 2010	SR-22/I-405/I-605	Dec. 2010
I-15 / SR-94	Jan. 2009	SR-57	Aug. 2010
I-805	July 2010	SR-91	Aug. 2010
		I-5	June 2012

Information as of June 2012

2.4. CSMP CORRIDORS WITH SIMULATION COMPONENT

Of the 45 CSMP corridors identified in Table 1, 31 have used traffic simulation tools to evaluate corridor performance and assess the operational impacts of proposed improvements. The various simulation models that have been developed and used as part of these evaluations are listed in Table 2.

Table 2 – Traffic Simulation Developed for CMSP Evaluations

Simulation Package	Corridor	Caltrans District
Macroscopic Model		
FREQ 12	I-880 Santa Clara County	4
	US-101 Marin County	4
	US-101 South (*San Mateo County*)	4
	SR-4	4
	SR-24	4
	I-80 East	4
	SR-1/SR-183	5
	SR-58	6
	I-215	8
Microscopic Model		
CORSIM	I-880 Santa Clara County	4
	I-205/I-5	10
Paramics	US-50 (*2 models*)	3
	SR-65	3
	SR-99 & I-5	3
	I-580/I-238 (*2 models*)	4
	I-880 Alameda County	4
	I-80 West	4
	SR-99 Urban	6
	I-405 Los Angeles County (*2 models*)	7
	I-405/SR-22/I-605 Orange County (*2 models*)	12
	SR-57	12
	I-5 Orange County	12
VISSIM	US-101 South (*Santa Clara County*)	4
	I-5 North	7
	I-5 South	7
	I-210	7
	I-10	8
	SR-91 Riverside	8
TransModeler	I-5 North Coast	11
	I-805	11
	SR-91	12
Hybrid Microscopic/Mesoscopic Models		
TransModeler	US-101 Santa Barbara / Ventura	5 & 7

Information as of June 2012

A total of 36 models are listed as several corridors developed multiple models. For instance, both a microscopic CORSIM and a macroscopic FREQ 12 model were used to evaluate the I-880 corridor in District 4. For the US-101 corridor in San Marin County, evaluations similarly relied on both a FREQ 12 macroscopic model and a VISSIM microscopic model. To simplify modeling tasks, the I-580/I-328 corridor in Alameda County (District 4), I-405 corridor in Los Angeles County (District 7) and I-405/SR-22/I-605 corridor in Orange County (District 12) were further split into two sections that were evaluated separately with the same simulation tool. On the other end, a joint simulation model was developed to evaluate operations along sections of the US-101 freeway located in Santa Barbara County (District 5) and Ventura County (District 7).

Among the 31 simulation-based CSMPs, Caltrans District staff directly performed the modeling for three corridors. These include the SR-1/SR-183 corridor in District 5, SR-58 corridor in District 6, and SR-99 Urban corridor in District 6. The first two efforts were conducted using the FREQ 12 macroscopic model, while the third used the Paramics microscopic model. All the remaining corridors were evaluated by private consulting firms. In some cases the firm leading the development of the CSMP also conducted the modeling, while in others a firm specializing in traffic simulation modeling was subcontracted by the CSMP prime contractor. Overall, 8 consulting firms were responsible for the simulation evaluations in 28 of the 31 CSMPs, which represent 90% of all modeling efforts.

Table 2 indicates that a variety of modeling approaches, ranging from macroscopic to microscopic and hybrid microscopic/mesoscopic, were used to conduct the CSMP operational evaluations. Microscopic modeling was by far the dominant approach, as it was used for 22 of the 31 evaluations. Within this group, the two most common simulators were Paramics and VISSIM, two well-established commercial tools. Only two CSMPs used CORSIM, a model that was once commonly used but which utilization is gradually fading, while three evaluation teams used TransModeler, a relatively recent traffic simulator. FREQ 12, a macroscopic model that have been used for more than 30 years but that is no longer supported by its initial developer (the University of California, Berkeley), was further used to support the evaluations for 9 corridors, i.e., in about 30% of the cases. Finally, a hybrid microscopic/mesoscopic approach was used for only one corridor. This effort relied on a new feature offered by TransModeler. Microscopic principles were used to model with high fidelity the freeway mainline and ramps while mesoscopic principles were used to model surrounding arterials at a lower resolution.

Table 3 – Unsuccessful CSMP Simulation Modeling Attempts

Caltrans District	Corridor	Initial Modeling Attempt	Final Model
3	SR-99/I-5	Paramics	*Modeling abandoned*
8	I-215	VISSIM	FREQ 12
5	SR-1/SR-183	TransModeler Hybrid Microscopic/Mesoscopic	FREQ 12
11	I-5 North Coast	TransModeler Hybrid Microscopic/Mesoscopic	TransModeler Microscopic
11	I-805	TransModeler Hybrid Microscopic/Mesoscopic	TransModeler Microscopic

Table 3 concludes this section by presenting modeling efforts that were eventually abandoned or for which the initial modeling approach was altered due to significant calibration difficulties. Five such efforts are listed. They include an attempt to develop a large Paramics model for the SR-99/I-5 corridor in District 3, a VISSIM model for the I-215 corridor in District 8, and attempts to develop a hybrid microscopic/mesoscopic model with TransModeler for the SR-1/SR-183 corridor in District 5, the I-5 corridor in District 11, and the I-805 corridor in District 11. Modeling of the SR-99/I-5 corridor was eventually abandoned due to significant difficulties in obtaining a calibrated model. Evaluations for the I-215 and SR-1/SR-183 corridors were eventually conducted using the FREQ 12 macroscopic model, while microscopic-only TransModeler models were eventually developed for the I-5 and I-805 corridors.

2.5. CSMP DEVELOPMENT PROCESS

Figure 2 presents the sequence of activities that were typically involved in the development of a CSMP. Key activities include:

1) Establishment of a corridor evaluation team.
2) Identification of regional transportation objectives.
3) Identification of corridor to be evaluated. In addition to freeways, the corridor may include highways and major local roads serving as alternate routes, rail service, bus service, intelligent transportation systems (ITS), carpool/vanpool, and key bicycle and pedestrian facilities.

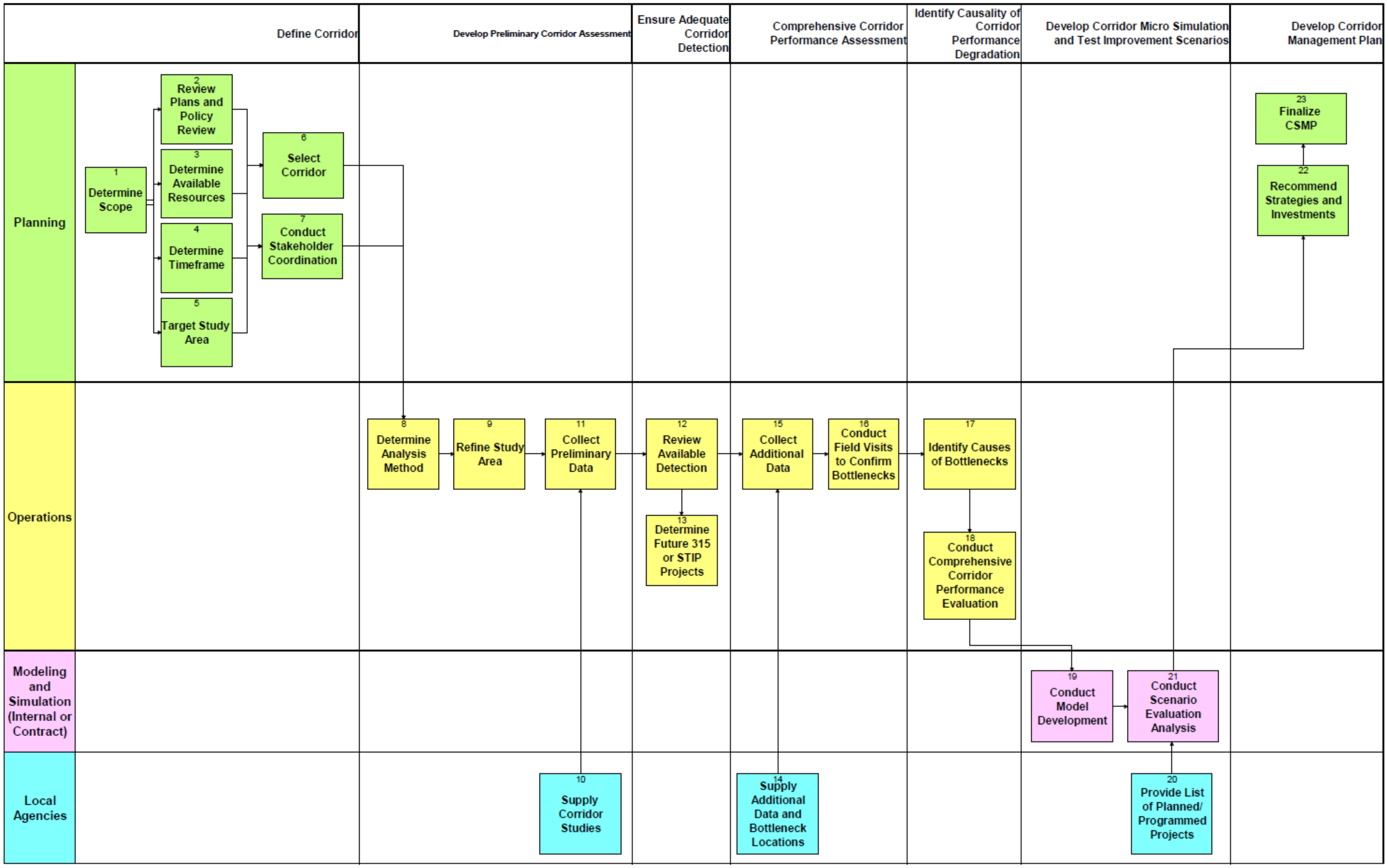

Figure 2 – Typical CSMP Development Process

(Source: System Metrics Group and Booz Allen Hamilton, 2010)

4) Execution of a preliminary performance assessment to gain an understanding of how the corridor is currently operating.
5) Evaluation of ability to collect the information required to conduct the evaluations.
6) Execution of a comprehensive performance assessment to locate main bottlenecks and problem areas along the corridor.
7) Identification of main causes of bottlenecks and corridor performance degradation.
8) Identification and evaluation of potential corridor improvement strategies.
9) Development of a traffic simulation model to evaluate the potential impacts of the identified candidate improvement strategies.
10) Preparation of a series of recommendations and a 20-year implementation plan for managing, operating, monitoring, and improving corridor system performance.
11) Development of a monitoring strategy that will allow the CSMP to be periodically updated based on a continuous analysis and performance monitoring process that takes into consideration deployed improvements and observed changes in travel demand.
12) Preparation of CSMP report.
13) Submission of CSMP report for acceptance/adoption by the Metropolitan Planning Organization (MPO) or Regional Transportation Planning Agency (RTPA), as well as cities and counties included in the corridor, for use as a guide for corridor management.

2.6. IMPROVEMENT STRATEGIES CONSIDERED

A range of potential corridor improvements were considered across all CSMP corridors. Potential improvements that were evaluated included capital infrastructure projects, operational system improvements, enhanced system management strategies, and, in a few cases, demand management strategies. Examples of potential corridor improvements that have been evaluated the CSMPs that have been completed so far include:

- **Capital investments**:
    - Construction of additional freeway lanes.
    - Introduction or expansion of High-Occupancy Vehicle (HOV) lanes.
    - Construction of auxiliary lanes.
    - Construction of new interchanges along freeway.
    - Widening of existing freeway on and off ramps.
    - Implementation of HOV bypass lanes on metered freeway ramps.
    - Modifications to geometric layout of existing interchanges.
    - Addition of truck climbing lanes.
    - Addition of left-turn and right-turn lanes at intersections.
    - Construction/improvement of bicycle lanes and pedestrian paths.

- **Operational improvements**:
    - Lane restriping.
    - Allowing the use of shoulder as additional traffic lane during congestion.

- Installation of traffic signals along arterials.
- Upgrades to existing traffic signal coordination.
- Interchange improvements.
- Introduction of ramp metering at freeway on-ramps.
- Coordinated ramp metering strategies, such as the Semi Actuated Traffic Metering System (SATMS) and San Diego Ramp Metering System (SDRMS).
- Conversion of HOV lanes into High-occupancy Toll (HOT) lanes.
- Implementation of Bus Rapid Transit (BRT).
- Provision of transit signal priority at intersections along arterials.

- **Enhanced system management strategies**:
  - Implementation of new or enhanced incident management response protocols to mitigate the effects of incidents on traffic conditions.
  - Emergency traffic re-routing plans.
  - Introduction/expansion of Freeway Service Patrol (FSP).
  - Restrictions on commercial vehicle operations along freeways and arterials.
  - Implementation of reversible lanes (managed lane system) along freeways.
  - Implementation of transit lanes.
  - Evaluation of pricing programs for goods movement/freight operations.

- **Demand management strategies**:
  - Use of changeable message signs to provide enhanced traveler information.

2.7. PERFORMANCE MEASURES CONSIDERED

The parameters that were used during the development of CSMPs to assess corridor performance and the effectiveness of improvement strategies typically fall into the following five categories:

- **Mobility** – Measures describing how well persons and goods move along a corridor. For instance, typical mobility measures include the time needed to travel between two points or the average speed at which travel occurs, incurred delays, and level-of-service (LOS) measures.
- **Productivity** – Measures describing the overall efficiency of a corridor with respect to its capacity of carrying vehicles, people and freight. While mobility measures focus on the severity of congestion and ease of travel, productivity measures are used to assess the overall quality of the transportation services provided.
- **Reliability** – Measures seeking to capture the relative predictability of travel times along specific road segments or between given origin-destination (O-D) pairs during a specific period across various days. While mobility measures assess average delays and travel times, reliability measures focus on how mobility varies from day to day. Reliability is very important for travelers as significant variations in travel times can have important effects on their travel plans and daily activities. It is also important for industries relying heavily on the movement of goods.
- **Safety** – Measures characterizing accident risks along roadway sections.
- **Preservation** – Measures assessing roadway pavement conditions and maintenance needs.
- **Cost effectiveness** – Measures assessing the cost-effectiveness of individual improvement strategies or bundle of strategies.

The following sub-sections provide more details about the specific metrics that have been used to evaluate the productivity, mobility, reliability, safety and preservation needs of each corridor. While the emphasis is on CSMPs that have involved the use of traffic simulators, the compilations and findings also reflect what has been done in other CSMP development efforts.

2.7.1. MOBILITY MEASURES

Table 4 compiles the metrics that have been used in the CSMP projects listed in Table 2 to assess mobility along each corridor. Similar to Table 5, the data distinguish metrics that have been used for the comprehensive performance assessments, typically using field data, and the metrics that have been used to assess future performance using simulation. Key productivity measures include:

- **Travel time** – Time taken by individuals or vehicles to travel a distance between two points along a corridor. Higher mobility is typically associated with lower average travel times.
- **Vehicle-hours of delay (VHD)** – Total delay incurred by all vehicles traveling within a study area.
- **Person-hours of delay (PHD)** – Total delay incurred by all persons traveling within a study area.
- **Mean system vehicle speed** – Parameter quantifying how fast vehicles travel on average across a study area. For a network or group of links, this parameter is typically calculated by simply dividing the total VMT measured across the area by the total VHT.

  Level of Service (LOS) – Parameter describing the quality of traffic flow. Depending on how it is calculated, LOS may be a reflection of observed travel speeds, travel times or flow interruptions. LOS is typically expressed as a letter grade ranging from "A" to "F", with "A" representing excellent, free flow conditions and "F" representing jammed, congested flow conditions. As a general rule, Caltrans sets a target of LOS C or D during peak traffic conditions, as such a LOS have been found to provide the highest level of throughput with the least traveler disruptions.

Travel time and delay are the most commonly used measures in CSMPs. Both parameters are related, as longer travel times along a corridor result in higher delays. LOS is also frequently used to characterize traffic operations at intersections or along arterials.

Delay expresses the amount of time lost due to congestion, traffic control devices, and other factors. From a theoretical standpoint, delay is calculated as the difference between the time it takes to travel between two reference points under observed conditions and the time it would have taken to travel over the same distance under free flow or specific reference conditions. In the CSMP studies, delay is typically reported as vehicle-hours of delay and commonly calculated using the equation below.

$$VHD = \begin{pmatrix} Vehicles\ Affected \\ per\ Hour \end{pmatrix} * \begin{pmatrix} Segment \\ Length \end{pmatrix} * (Duration) * \left[\frac{1}{CongestedSpeed} - \frac{1}{ThresholdSpeed}\right]$$

Where: *Vehicles affected per hour* = Number of vehicles affected by congestion.
Segment length = Distance under which the congested speed prevails.
Duration = Duration of the congested period, in hours.
Congested speed = Average speed of traffic while speed is below the threshold.
Threshold speed = Speed below which travelers are assumed to experience delay.

Table 4 – Mobility Measures Examined in CSMPs Involving Traffic Simulation

Corridor	Caltrans District	Comprehensive Performance Assessment				Simulation-based Forecasts			
		Travel Time	Speed	Delay	LOS	Travel Time	Speed	Delay	LOS
I-80 East	4	Average travel time	-	VHD by segment and peak period	-	n/a	n/a	n/a	-
I-80 West	4	Average travel time	Average speed	VHD by day of week	Intersection LOS	-	Average speed by facility type	VHD by facility type	-
I-580	4	Average travel time	Mean Person speed	VHD, PHD, mean delay per person	-	-	Mean Person Speed	PHD, mean delay per person	-
I-880	4	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	Freeway and Intersection LOS	Average travel time	Average speed, Speed contour plot	VHD by facility, vehicle type, and bottleneck area	Freeway and intersection LOS
SR-4	4	Average travel time	Contour plot	VHD at 35-mph and 60-mph thresholds	-	Average travel time	Peak hour speed	VHD (total)	-
SR-24	4	Average travel time	Average Speed	VHD at 35-mph and 60 mph threshold	-	Average Travel Time	Average speed	VHD at 35-mph and 60-mph threshold, delay index, congestion delay	-
US-101 North	4	Average travel time	Average speed	VHD and PHD relative to free-flow speed	-	-	Average speed	VHD and PHD relative to f-f speed	-
US-101 South	4	Average travel time	Average speed	VHD at 50-mph thresholds	-	Average travel time	Average speed	VHD at 50 mph threshold, delay per vehicle, congested lane-miles	-
SR-1 / SR-183	5	Average travel time	Average Speed	Total VHD	LOS by segment	Average travel time	Average Speed	Average delay per vehicle	LOS by segment
US-101	5, 7	Average travel time	-	VHD, delay as percentage of travel time	Arterial LOS	Average travel time	-	Daily VHD, delay as percentage of travel time	-
SR-58	6	Average travel time	Average speed	VHD at 35-mph threshold	LOS by segment	n/a	n/a	n/a	LOS by segment
SR-99	6	Average travel time	Average speed	VHD at 35-mph threshold	LOS	Average travel time	Average speed, contour plot	Daily VHD	LOS
I-5 Los Angeles	7	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
I-210	7	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-

Table 4 – Mobility Measures Examined in CSMPs Involving Traffic Simulation (cont'd)

Corridor	Caltrans District	Comprehensive Performance Assessment				Simulation-based Forecasts			
		Travel Time	Speed	Delay	LOS	Travel Time	Speed	Delay	LOS
I-10	8	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
I-15	8	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	n/a	n/a	n/a	-
I-215	8	Average travel time	Contour plot	VHD at 35 mph and 60 mph thresholds	-	-	Average speed	Freeway VHD, delay as percentage of freeway travel time	-
SR-91	8	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35 mph and 60 mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
I-205/I-5	10	Average travel time	Contour plot	VHD by segment	Intersection LOS	Average travel time	Average speed	VHD by segment	-
I-5	11	Average travel time	Average speed by interchange, Contour plot	VHD by month, average VHD by time of day, duration of Congestion per day at 35-mph threshold	Arterial LOS	Average travel time	Contour plot	VHD per direction at 35-mph and 60-mph thresholds	-
I-805	11	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
I-405/ SR-22	12	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
SR-57	12	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-
SR-91	12	Average travel time	Contour plot	VHD by bottleneck area and delay/lane-mile at 35-mph and 60-mph thresholds	-	-	Contour plot	VHD by facility, vehicle type, and bottleneck area	-

While the above formula is commonly used, differences exist in the value assigned to the threshold speed below which delay is assumed to be incurred. A common practice is to equate free-flow conditions to travel at or near speed limit. If the speed limit is used as a threshold, only vehicles traveling below the speed limit are thus assumed to incur delays.

To account for the fact that travel at speeds slightly lower than the posted speed limit may not be perceived as a delay by the traveling public, lower speed thresholds are often used. In evaluation projects conducted by Caltrans, two specific thresholds are frequently used for assessing delays:

- **60 mph delay threshold** – On most freeway segments, delay is only assumed to be incurred if travel speeds drop below 60 mph. However, this threshold can be lowered for freeway segments having posted speed limits below 65 mph.
- **35 mph delay threshold** – Caltrans define congested conditions as traffic moving at a speed of 35 mph for 15 minutes or more. Many CSMP studies thus estimated delay incurred during congestion by using a 35-mph reference speed.

2.7.2. PRODUCTIVITY MEASURES

Table 5 compiles the metrics that have been used to assess corridor productivity in the simulation-based CSMPs listed in Table 2. The data distinguish the performance measures that have been used for comprehensive performance assessments, which typically seek to assess existing conditions along the corridor using field data, and measures that have been used to assess future performance using simulation. Key productivity measures that were considered include:

- **Vehicle-Miles Traveled (VMT)** – VMT compiles the total distance traveled by all vehicles within a study area. This parameter provides an indication of the total travel demand within an area. For instance, changes in VMT can result from a change in the number of trips being made, or vehicles making longer or shorter trips to reach their destinations.
- **Vehicle-hours of travel (VHT)** – VHT compiles the total amount of time expended by vehicles traveling within a study area. A decrease in VHT generally indicates improved system performance, while an increase indicates reduced performance. For instance, a reduction in VHT can result from fewer vehicles traversing the area, vehicles making shorter trips, or vehicles experiencing fewer delays along their travel path.
- **Person-miles of travel (PMT)** – Total distance traveled by individuals within a corridor.
- **Person-hours of travel (PHT)** – Time expended by individuals traveling within an area.
- **Lane Capacity** – Maximum vehicular flow that can traverse a highway lane over an hour. The capacity of a roadway section typically varies based on roadway characteristics (number of lanes, lane width, curvatures, etc.). Capacity can also vary due to weather conditions and various environmental factors. To provide a common base of comparison, many CSMP studies have simply assumed a fixed capacity value for freeway segments, typically 2000 vehicle per hour (vph) per lane. This is a conservative estimate, as the HCM 2000 indicates that freeway capacities can reach 2400 vph per lane.
- **Throughput** – Maximum number of vehicles observed to traverse a highway lane during an hour. In ideal networks, throughput should correspond to capacity. However, throughput is often lower than the nominal capacity of a roadway segment due to various behavioral factors.

Table 5 – Productivity Measures Examined in CSMPs Involving Traffic Simulation

Corridor	Caltrans District	Comprehensive Performance Assessment	Simulation-Based Forecasts
I-80 East	4	-	n/a
I-80 West	4	VMT, VHT, Lost lane-miles	VMT, VHT by facility type
I-580	4	PMT, PHT, Lost lane-miles	PMT, PHT
I-880	4	Lost lane-miles by bottleneck area	--
SR-4	4	VMT, VHT	Congested lane-miles, congestion duration
SR-24	4	--	Congested lane-miles
US-101 North	4	Lost lane-miles	VMT, VHT, PMT, PHT
US-101 South	4	Lost lane-miles	Lost lane-miles, VMT, VHT
SR-1/SR-183	5	VMT	-
US-101	5,7	Lost lane-miles	-
SR-58	6	--	n/a
SR-99	6	Lost lane-miles	-
I-5 Los Angeles	7	Lost lane-miles by bottleneck area	-
I-210	7	Lost lane-miles by bottleneck area	-
I-405	7	Lost lane-miles by bottleneck area	-
I-10	8	Lost lane-miles by bottleneck area	-
I-15	8	Lost lane-miles by bottleneck area	NA
I-215	8	Lost lane-miles	VMT, VHT
SR-91	8	Lost lane-miles by bottleneck area	-
I-205/I-5	10	Lost lane-miles	Volume served, queue lengths
I-5	11	VMT, VHT	Congestion duration, VMT
I-805	11	Lost lane-miles by bottleneck area	-
SR-22/I-405	12	Lost lane-miles by bottleneck area	-
SR-57	12	Lost lane-miles by bottleneck area	-
SR-91	12	Lost lane-miles by bottleneck area	-

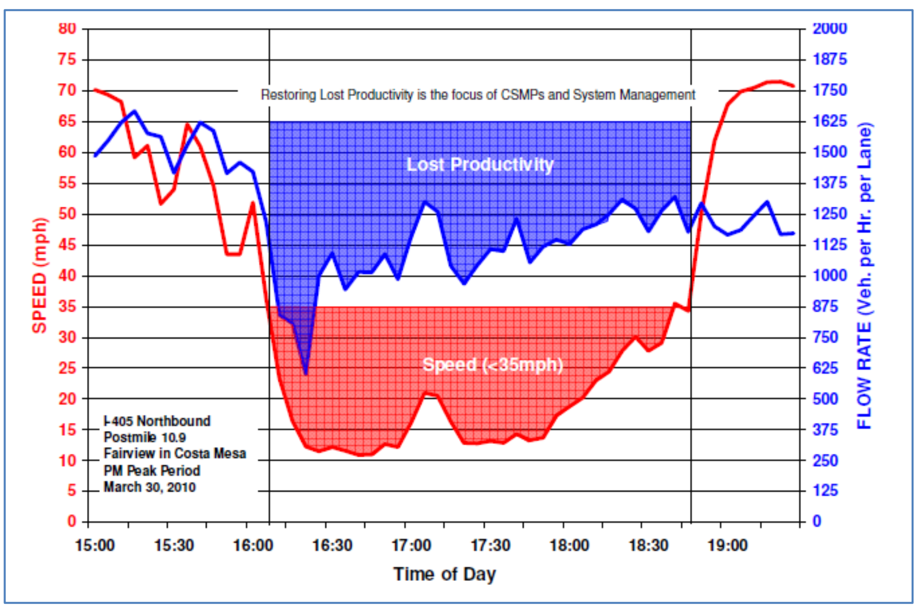

Figure 3 – Lost Productivity Concept

- **Lost Productivity** – Capacity lost due to flow breakdown, typically determined by calculating the difference between the observed traffic volumes on a lane or road segment under congested conditions and the flow capacity for the lane or segment. Figure 3, which has been reproduced from the I-805 Final CSMP Report, graphically illustrates this concept.
- **Congested lane-miles** – Total number of miles across lanes that experience congestion.
- **Lost Lane Miles** – Theoretical capacity that would need to be added to a road segment to achieve maximum productivity. For example, losing six lane-miles implies that adding a new lane along a six-mile section of freeway would be needed to maximize productivity. This parameter is related to the loss productivity and is typically calculated as follows:

$$LostLaneMiles = \left(1 - \frac{Observed\ Lane\ Throughput}{Lane\ Capacity}\right) * Lanes * Congested\ Lane - Miles$$

- **Percent utilization of facility** – Ratio of observed traffic volume to nominal flow capacity.

2.7.3. RELIABILITY MEASURES

Table 6 compiles the reliability measures that were compiled for the CSMP corridors listed in Table 2. Key reliability measures that were considered include:

- **90th or 95th percentile travel times** – Longest travel times that could be observed on the heaviest travel days based on the observed variability of travel times.
- **Mean travel times** – Statistical average of all observed travel times within a given period.
- **Median travel times** – Travel time value at which 50 percent of individual travel time values are below and 50 percent above.
- **Planning time index** – A measure of the extra time that travelers must plan above the free-flow travel time to ensure that they reach their destination on time 95% of the time. This parameter differs from the buffer index in the fact that it includes both typical and unexpected delays. It compares near-worst case travel time to the travel time that would be experienced in light or free-flow traffic, while the buffer index utilize the average travel time as a reference. The planning time index is usually estimated using the following formula:

$$Planning\ Time\ Index = \frac{95\%\ TravelTime}{Free - FlowTravelTime}$$

- **Buffer index** – A measure of the extra time above the reported average travel time that travelers must budget to ensure they will reach their destination on time. As shown in the equation below, this parameter is calculated by dividing the difference between the 90th or 95thpercentile and mean travel times by the mean travel time. It is usually expressed as a percentage. Higher values typically mean higher travel time variability. For example, a buffer index of 40 percent means that for a trip that usually takes 20 minutes a traveler should budget an additional 8 minutes to ensure on-time arrival (barring extremely rare instances of congestion) to compensate for recurrent and non-recurrent congestion.

$$BufferIndex = \frac{95\%\ TravelTime - MeanTravelTime}{MeanTravelTime}$$

Table 6 – Reliability Measures Examined in CSMPs Involving Traffic Simulation

Corridor	Caltrans District	Comprehensive Performance Assessment	Simulation-Based Forecasts
I-80 East	4	-	-
I-80 West	4	Average and 95th percentile travel times	-
I-580	4	Average and 95th percentile travel times, buffer index	Average and 95th percentile travel times, buffer index [1]
I-880	4	Average travel time, 70th, 85th, 95th and 99th percentile travel times buffer index	-
SR-4	4	Average and 95th percentile travel times, buffer index	-
SR-24	4	Average and 95th percentile travel times, buffer index	-
US-101 North	4	Average and 95th percentile travel times, buffer index	-
US-101 South	4	Average and 95th percentile travel times, buffer index by segment	Average and 95th percentile travel times, buffer index by segment
SR-1/SR-183	5	-	-
US-101	5, 7	-	-
SR-58	6	-	-
SR-99	6	-	-
I-5 Los Angeles	7	Average and 95thpercentile travel times	-
I-210	7	Average and 95th percentile travel times	-
I-405	7	Average and 95th percentile travel times	-
I-10	8	Average and 95th percentile travel times	-
I-15	8	Percentage of variation in travel times	-
I-215	8	Average, 90th, and 95thpercentile travel times, buffer index	-
SR-91	8	Average and 95th percentile travel times	-
I-205/I-5	10	Average Index, mean and 95th percentile travel times	-
I-5	11	Mean and median Travel Times, buffer index	-
I-805	11	Average and 95th percentile travel times, buffer index	-
I-405/SR-22	12	Average and 95th percentile travel times	-
SR-57	12	Average and 95th percentile travel times, buffer index	-
SR-91	12	Average and 95th percentile travel times, buffer index	-

[1] Reliability assessed by feeding simulation results into regression equations developed from field data.

For the various corridors, reliability measures were typically only estimated if data characterizing travel times or speeds along the corridor were available for a sufficiently long period of time. Depending on the corridor, analyses were made using data covering either multiple days or multiple months. Reliability was generally not assessed where insufficient time series data were not available.

It was finally observed that reliability was typically only assessed as part of the initial comprehensive performance assessments. While the stochastic nature of traffic simulations models could be used to assess reliability, this was not done so. A likely explanation is linked to uncertainties that are often expressed regarding the ability of simulation models to reproduce the true variability of observed traffic conditions, and thus, to produce reliable reliability estimates. There are suggestions that the stochastic nature of simulated traffic volumes may be lower than reality, resulting in a certain inability to accurately model the true variability of travel times without artificially adding perturbations to the O-D flows. The I-580 East and US-101 San Mateo CSMPs are the only corridors for which simulation results were used to assess reliability. In both cases, the 95th percent travel times and travel time standard deviation were assessed by feeding simulation results into regression equations that had been developed from field data.

2.7.4. SAFETY MEASURES

Table 7 compiles the performance measures that were considered to assess safety along the CSMP corridors listed in Table 2. Key metrics that were considered only include the following two parameters:

- **Number of accidents –** Number of accidents that have happened over a given period. This number may be compiled by collision type, road segment, or time period.
- **Accident rate** – Number of accidents per million vehicle miles traveled.

Table 7 – Safety Measures Examined in CSMPs Involving Traffic Simulation

Corridor	Caltrans District	Comprehensive Performance Assessment	Simulation-Based Forecasts
I-80 East	4	Accident rates by segment, number of collisions by time of day, percent of accident type by location	-
I-80 West	4	Accident rates by segment	-
I-580	4	Accident rates by segment and accident type	-
I-880	4	Accident rate by segment	-
SR-4	4	Accident rates by segment, accident type, month of year, day of week and time of day	-
SR-24	4	Accident rates by segment, accident type, month of year, day of week and time of day	-
US-101 North	4	Accident rates by segment and type of accident	-
US-101 South	4	Accident rate by segment	Forecasted rates
SR-1/SR-183	5	Accident rate by segment	-
US-101	5, 7	Accident rate by segment	-
SR-58	6	Accident rate by segment	-
SR-99	6	Accident rates by segment and accident type	-
I-5 Los Angeles	7	Number of accidents by month, weekday/weekend	-
I-210	7	Accident rates by segment, month, weekday/weekend, and type of collision	-
I-405	7	Accident rates by month and type of accident	-
I-10	8	Accident rates by month, weekday/weekend	-
I-15	8	Number of accidents by year	-
I-215	8	Number of accidents by time of day, day of week, segment, collision type, and collision factor	-
SR-91	8	Accident rates by month, weekday/weekend, type of collision	-
I-205/I-5	10	Number of accidents, accident rate by segment	-
I-5	11	Accident rate by type of accident, number of accidents by time of day	-
I-805	11	Number of accidents by month, weekday/weekend	-
I-405/SR-22	12	Number of accidents per month	-
SR-57	12	Number of accidents, accident rate	-
SR-91	12	Number of accidents, accident rate by segment	-

Note: *Segment definition varied across the various corridors. Some corridors defined segments based on the location of bottlenecks while others only considered key interchanges.*

Across the various CSMP corridors, safety statistics and trends were typically derived from field observations. A primary source of information was Caltrans' Traffic Accident Surveillance and Analysis System (TASAS). TASAS is a records system containing an accident database linked to a highway database. The accident database contains records of accidents, while the highway database contains descriptions of highway segments, intersections and ramps, access control, traffic volumes, and other data. For studies covering local street and roads, additional accident data were retrieved from local accident recording systems.

While safety improvements were an underlying CSMP goal, safety measures cannot typically be evaluated from traffic simulation models due to the fact that such models are intrinsically built to be collision-free. Situations that would result in vehicles colliding in reality are simply ignored. For instance, some models can tolerate that two vehicles partially occupy the same space. Other models implement instead arbitrary position corrections or temporary unrealistic driver behavior to prevent such a situation or two vehicles from colliding. Due to these limitations, safety evaluations for the CSMP corridors were almost exclusively based on field observations. The CSMP for the US-101 South corridor in San Mateo County is the only CSMP for which safety assessments were made using simulation data. This assessment first used simulation results to forecast changes in operational speeds and VMT along the corridor. Future collision rates were then projected by adjusting current collision rates based on the anticipated changes in operational speeds and VMT.

2.7.5. PRESERVATION MEASURES

Table 8 compiles the system measures that have been used to assess system preservation in the CSMP corridors listed in Table 2. The two primary preservation measures considered are:

- **Distressed lane-miles** – Miles of roadway lanes showing poor structural condition or poor ride quality that may require major rehabilitation or replacement. This parameter allows for distinction between segments that may require only preventive maintenance at relatively low costs and those that may require major rehabilitation or replacement at significantly higher costs. All segments that require major rehabilitation or replacement, as well as those with poor ride quality, were considered to be distressed.

- **International Roughness Index (IRI)** – IRI distinguishes between smooth-riding and rough-riding pavement. The distinction is based on measuring the up and down movement of a vehicle over pavement. A pavement is considered good or smooth-riding when movements are less than 95 inches per mile (in/mi), acceptable when movements are between 95 and 170 in/mi, and unacceptable or rough-riding when movements are above 170 in/mi.

While parameters characterizing pavement condition status or ride quality are part of CSMP operational evaluations, such parameters cannot be obtained from simulation models. As a result, all preservation metrics were estimated exclusively from field data and only used to assess current system performance.

Table 8 – Preservation Measures Examined in CSMPs Involving Traffic Simulation

Corridor	District	Comprehensive Performance Assessment	Simulation-Based Forecasts
I-80 East	4	Distressed lane-miles	-
I-80 West	4	Distressed lane-miles, IRI	-
I-580	4	Distressed lane-miles, IRI	-
I-880	4	Distressed lane-miles, IRI	-
SR-4	4	-	-
SR-24	4	-	-
US-101 North	4	Distressed lane-miles	-
US-101 San Mateo	4	-	-
SR-1/SR-183	5	-	-
US-101	5 and 7	Distressed lane-miles, IRI	-
SR-58	6	% priority distressed areas	-
SR-99	6	% priority distressed areas	-
I-5	7	Distressed lane-miles, IRI	-
I-210	7	Distressed lane-miles, IRI	-
I-405	7	Distressed lane-miles, IRI	-
I-10	8	Distressed lane-miles, IRI	-
I-15	8	Distressed lane-miles, IRI	-
I-215	8	Distressed lane-miles, IRI	-
SR-91	8	Distressed lane-miles, IRI	-
I-205/I-5	10	Distressed lane-miles	-
I-5	11	-	-
I-805	11	Distressed lane-miles, IRI	-
SR-22/I-405/I-605	12	Distressed lane-miles, IRI	-
SR-57	12	Distressed lane-miles, IRI	-
SR-91	12	Distressed lane-miles, IRI	-

2.7.6. COST EFFECTIVENESS MEASURES

Various metrics can be used to compare the cost-effectiveness of proposed improvements projects. Examples of frequently used metrics include:

- **Cost-Benefit Analysis (CBA)** – Technique attempting to quantify and compare the economic advantages and disadvantages associated with a particular project. The appeal of this technical is associated with the monetizing of benefits, which makes it is possible to compare or aggregate different categories of benefits with one another, and with the costs of the project. When using this technique, various projects can be compared using a benefit over cost ratio, or by simply considering the net benefits, i.e., the difference between the benefits and costs.
- **Cost Effectiveness Analysis (CEA)** – Technique seeking to find the best alternative that minimizes the costs of achieving a desired result. A cost-effectiveness analysis is often performed when the objectives of a project have been identified and the only remaining question is to find the least cost−option to arriving at these objectives. It is also applied for projects for which some of the benefits can be difficult to monetize.

Within the CSMP operational evaluation framework, the preferred approach to assess the effectiveness of proposed improvements has been to associate a benefit/cost ratio to improvement bundles. Where a benefit/cost ratio was not evaluated, the effectiveness of proposed improvements was primarily assessed against their ability to reduce delays or travel times along the corridor.

Where a cost/benefit analysis was performed, the analyses were typically performed using the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C model) developed by Caltrans' Office of Transportation Planning. The same tool has been used by Caltrans to analyze proposed projects for the interregional portion of the State Transportation Improvement Program (STIP) and the State Highway Operations and Protection Program (SHOPP). A particular advantage of the Cal B/C model is that it requires relatively minimal inputs since it is populated with many California-based default values. Key required parameters include basic information about the project being evaluated, the roadway configuration under the no-build and build alternatives, traffic demand, and project costs.

Cal-B/C is implemented as an Excel-based spreadsheet tool structured to analyze several types of improvement projects along corridor where a highway facility or transit service already exists. Figure 4 illustrates a typical output from the model. The benefits associated with proposed improvements are calculated over a 20-year life cycle for the existing traffic, induced traffic, and traffic that may be diverted from a parallel highway or transit service. Peak and off-peak benefits are further estimated, as well as highway impacts for both HOV and non-HOV vehicles. Estimated travel time savings are based on a speed-congestion relationship adapted from the 1997 Highway Capacity Manual that assumes a capacity of 2000 vph for general-purpose freeway lanes and 1600 vph for HOV lanes. Outputted economic measures include life-cycle costs and benefits, net present value, a benefit/cost ratio, an estimated rate of return on investment, and an estimated payback period. Monetized benefits from reduced travel times, reduced vehicle operating costs (fuel and non-fuel costs), fewer accidents, and reductions in vehicle emissions are also outputted.

3

INVESTMENT ANALYSIS

SUMMARY RESULTS

Life-Cycle Costs (mil. $)	$429.4
Life-Cycle Benefits (mil. $)	$1,169.3
Net Present Value (mil. $)	$740.0
Benefit / Cost Ratio:	2.7
Rate of Return on Investment:	19.6%
Payback Period:	5 years

ITEMIZED BENEFITS (mil. $)	Average Annual	Total Over 20 Years
Travel Time Savings	$48.4	$967.8
Veh. Op. Cost Savings	$7.3	$145.3
Accident Cost Savings	$0.0	$0.0
Emission Cost Savings	$2.8	$56.3
TOTAL BENEFITS	$58.5	$1,169.3
Person-Hours of Time Saved	5,602,400	112,048,009
Additional CO_2 Emissions (tons)	-33,501	-670,014
Additional CO_2 Emissions (mil. $)	-$1.0	-$20.3

Figure 4 – Cal B/C Analysis Output Example (I-805 CSMP, Scenario 3A)

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3. REVIEW OF TRAFFIC SIMULATION MODELING CAPABILITIES

This section provides a review of the current state-of-practice regarding the use of traffic simulation in transportation corridor studies. The purpose of this review is to provide background information on simulation principles to readers who may not have extensive knowledge in this field. Elements presented herein include:

- Traffic simulation modeling approaches;
- Travel demand models;
- Integrated modeling suites;
- Traffic simulation process elements;
- Data requirements;
- Calibration needs;
- Number of simulation runs required to evaluate scenarios;
- Reporting capabilities; and
- Comparative assessment of modeling approaches.

3.1. MODELING APPROCHES

Simulation models are usually classified according to the level of detail at which they represent the traffic stream. They are typically categorized in one of the following three broad groups, which are schematically illustrated in Figure 5:

- **Macroscopic models** – Models simulating traffic flow behavior using average aggregate traffic stream characteristics, such as flow rate, speed and traffic density.
- **Microscopic models** – Models simulating the movement of individual vehicles through the application of driver behavioral models.
- **Mesoscopic models** – Models simulating the movement of individual vehicles using simplified vehicle behavioral models, often based on macroscopic principles.

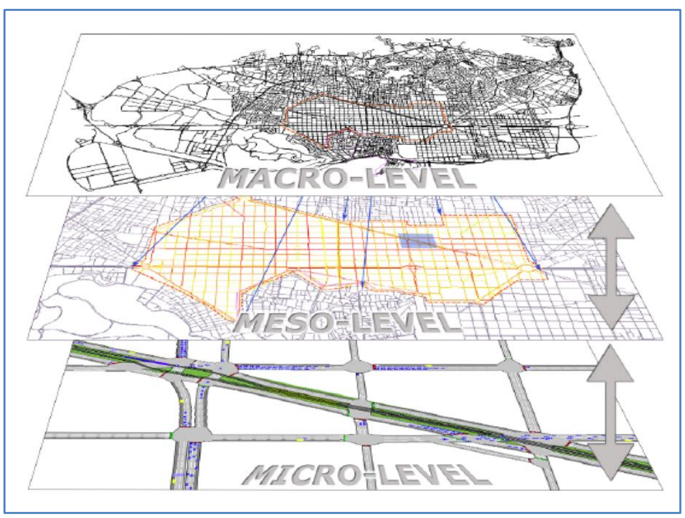


Figure 5 – Macroscopic, Mesoscopic and Microscopic Modeling Concepts
(Source: Cambridge Systematics, 2007)

More detailed descriptions of each approach, as well as the identification of commercial software implementing these approaches, are provided in the subsections that follow.

3.1.1. MACROSCOPIC MODELS

Macroscopic models simulate traffic flow behavior by taking into consideration aggregate traffic stream characteristics and the relationships among these characteristics. Flow rate, speed, and density are the stream characteristics most commonly considered. Macroscopic models do not explicitly model individual vehicles, but rather focus on average flow behavior. In these models, traffic progression along roadways is typically modeled using an approach similar to how fluids are modeled to travel through pipes. Stream behavior is determined using deterministic equations that utilize flow conservation principles and define how traffic disturbances or shockwaves propagate along roadways.

Table 9 – Macroscopic Simulation Tools

Model	Latest Release	Date	Developer	Information Website / Reference
FREQ 12	3.02	09/2006	University of California, Berkeley	May and Leiman (2005)
TRANSYT-7F	11.3	12/2008	McTrans Center, University of Florida	http://mctrans.ce.ufl.edu/featured/transyt-7f/
Aurora	--	01/2012	University of California, Berkeley	http://gateway.path.berkeley.edu/topl/index.html

Information as of June 2012

Table 9 lists macroscopic models that were available at the time of this study. Most of these models were developed to test the impacts of operational strategies on high-level road networks (Dowling *et al,* 2004; Burghout, 2004; Sbayti and Roden, 2010). Due to their simplified modeling, macroscopic models are generally less computationally and data intensive than microscopic or mesoscopic models. They are therefore well-suited for executing fast simulations and modeling large networks. However, as a result of the increasing ability to run microscopic tools on regular desktop computers, the use of macroscopic models has significantly declined over the past decade.

Among the models listed in Table 9, only FREQ 12 has been used to support the CSMP operational evaluations. This model simulates freeway operations based on classical speed-flow-density relationships. Since its initial release in the 1970s, it has been used extensively by Caltrans District staff, as well as by other transportation agencies and consultants, to evaluate freeway improvement projects. It can be used to analyze the impacts of HOV facilities, ramp control optimization, normal and priority entry control strategies, time-varying reconstruction activities, freeway incidents, geometric changes, freeway-arterial diversions, future growth scenarios, and various information system configurations. However, as of late 2010, this model was no longer being developed by the University of California, Berkeley, and thus is no longer available for purchase or download.

TRANSYT-7F is another macroscopic model that once enjoyed extensive popularity prior to the advent of microscopic models. This simulation tool was developed in the mid-1970s to support the optimization of traffic signals and the operational evaluation of signalized arterials. Within TRANSYT-7F, traffic operations are evaluated by propagating cyclic flow profiles from one intersection to the next while considering platoon dispersion and other factors.

The only recent macroscopic model is the Aurora Road Network Modeler (Chow *et al.*, 2009), which is currently being developed at the University of California at Berkeley as part of the Tools for Operational Planning (TOPL) suite. It is meant to be used as a performance analysis support tool for the management of freeways and arterials. One of its main design goals is to help traffic operations engineers conduct real-time evaluations of operational improvement strategies, such as ramp metering, ramp capacity extension, utilization of shoulder lanes as additional travel lanes, implement of variable speed limits (VSL), utilization of changeable message sign as information dissemination tools, utilized of managed lane systems, and implementation of auxiliary lanes. However, due to its recent development, very few studies have so far relied on this model to conduct evaluations.

3.1.2. MICROSCOPIC MODELS

Microscopic models simulate the movements of individual vehicles, typically on a second-by-second or more refined basis. Interactions between vehicles, as well as between vehicles and roadway hazards, are based on seta of behavioral rules that attempt to recreate real-world behavior. Key elements that are typically modeled include:

- Behavior of vehicles not affected by other vehicles (lead behavior);
- Behavior of vehicles in proximity of other vehicles (car-following behavior);
- Lane selection and lane changing behavior; and
- Gap acceptance behavior where conflicts arise with other vehicles, pedestrians, or other simulation objects.

Most microscopic models are stochastic in nature. Stochastic effects are obtained by allowing the characteristics of various objects to be determined by randomly sampling values from given probability distributions, most commonly a normal distribution. Elements commonly determined through such a process include vehicle characteristics, such as vehicle type, age, weight, accelerating power, and occupancy, and various driver behavior characteristics, such as desired speed, acceptable gap, and awareness of surrounding vehicles.

Microscopic models are particularly well-suited to the analysis of scenarios where detailed vehicle interactions are an important focus, such as the operation of actuated traffic signals, freeway merges, weaving sections, and high-occupancy vehicle lanes. In recent years, many models have also added the capability to simulate bicycles and pedestrians, thus enabling more realistic evaluations of multi-modal transportation systems. Another emerging feature is the capability for vehicles to adjust their travel path within a network in response to changing traffic conditions. In models offering this feature, path selection can typically be made using a simple all-or-nothing or a stochastic path selection algorithm. In most cases, route selection is determined based on an estimation of travel costs to reach a destination using recent travel times, travel distance, and other out-of-pocket costs such as tolls as cost variables

Table 10 lists the microscopic tools that could be used to model freeway corridors as of June 2012. Since the intent was to identify the main commercial models that could be used, the list does not necessarily include all available models. Among the listed models, CORSIM is the oldest. This model was the dominant simulation tool in the United States in the early 2000s. However, it has since been replaced in professional practice by VISSIM and PARAMICS. TransModeler and AIMSUN are more recent models that are steadily growing in popularity. Integration and Transims are models that are less frequently used in professional practice but that have some popularity in academic circles.

Table 10 – Available Commercial Microscopic Simulation Tools

Model	Latest Release	Date	Developer	Information Website / Reference
VISSIM	5.4	11/2011	PTV AG	http://www.vissim.de/index.php?id=1801
Paramics	6.9	05/2012	Quadstone Paramics, Ltd.	http://www.paramics-online.com/
AIMSUN	7.0	11/2011	Transport Simulation Systems	http://www.aimsun.com/
TSIS-CORSIM	6.2	02/2010	McTrans Center, University of Florida	http://mctrans.ce.ufl.edu/featured/tsis/version5/corsim.htm
TransModeler	2.6	06/2010	Caliper Corporation	http://www.caliper.com/transmodeler/default.htm
Transims	4.0.8	01/2011	Los Alamos National Lab – Now offered as open-source	http://code.google.com/p/transims/
S-Paramics	2011.1	11/2011	SIAS Transport Planners	http://www.sias.co.uk/ng/sparamicshome/sparamicshome.htm
Integration	2.3	02/2010	Virginia Tech Transportation Institute	http://filebox.vt.edu/users/hrakha/Software.htm
SimTraffic	8	2011	Trafficware	http://www.trafficwareinc.com/transportation/product/simtraffic-8-0

Information as of June 2012

A unique feature of the TRANSIMS model is its utilization of a cellular automata approach, instead of continuous links, to simulate traffic movements. This approach divides each link into cells that can contain only one vehicle. Within this environment, vehicles accelerate, decelerate, maintain speed or change lanes on the basis of the status of nearby cells. TRANSIMS was developed to help state departments of transportation and metropolitan planning organizations with their travel forecasting and transportation planning tasks. The model can build synthetic populations based on census and survey data, estimate activities for all individuals and households, plans multimodal trips satisfying those activities, assign specific routes to the generated trip, and simulate the movement of vehicles, pedestrians, and transit vehicles over the modeled transportation system.

While S-Paramics bares a name similar to Quadstone's Paramics, the two models are different. They do, however, share a common ancestry. Paramics was originally created in 1986 by SIAS with the assistance of staff from the University of Edinburgh. In 1996, several of the university's staff departed to form Quadstone and a joint-venture with SIAS to promote the development of Paramics. However, this joint-venture was dissolved in 1998 when SIAS and Quadstone failed to agree on a direction of development for Paramics. As a result SIAS continued to develop S-Paramics, while Quadstone pursued the development of what is now called Paramics.

While SimTraffic is included in the list of microscopic models, it should be noted that this tool was primarily developed to evaluate the operation of signalized and unsignalized intersections as a companion tool to the Synchro traffic signal optimization software. However, recent versions of the simulation model have added some capabilities to simulate freeway sections.

While all the listed models are designed to simulate the movements of individual vehicles, they do so through the implementation of slightly different driver behavior models. Consequently, different models will often produce slightly different results when used to evaluate similar scenarios. These differences have resulted in many attempts to identify which model may better represent real-world behavior. The professional literature offers various studies attempting to evaluate and compare the accuracy of the various models listed in Table 10 (for instance, Transportation System Systems, 2000; Jones *at al.*, 2004; Boile and Ozbay, 2005). However, while these studies present valuable assessments, it should be kept in mind that the evaluations are specific to the capabilities offered by each model at a specific point in time. Since simulation models are continuously evolving, issues reported within a specific study may no longer exist or be relevant.

3.1.3. MESOSCOPIC MODELS

Mesoscopic models combine the properties of microscopic and macroscopic models. They are somewhat less consistent than microsimulation tools, but are generally thought to be superior to macroscopic analysis techniques. They still simulate individual vehicles, but describe their activities and interactions based on aggregate (macroscopic) relationships. In most models, travel times along individual roadway links are based on an assumed speed-flow relationship describing the general behavior of all vehicles on the link. Some models also retain some lane selection behavior to replicate queuing at intersections. Typical applications of mesoscopic models are for evaluations of traveler information systems. The simplified behavioral relationships allow the models to execute simulations across large networks much quicker than microscopic models.

Table 11 provides a list of the mesoscopic models that were commercially available at the time of the study. Most of the listed models were initially developed to study dynamic traffic assignment procedures within large transportation networks. Many were subsequently expanded to predict responses to various traffic control measures and information dissemination strategies.

In Table 11, DYNASMART-P, DYNAMIT and TransModeler are the most commonly-known models. DYNASMART-P simulates the movements of individual vehicles, but moves each vehicle along roadway links using macroscopic traffic flow relations. In DYNAMIT, individual vehicles are grouped into cells, with the behavior of vehicles within each cell controlled by speed-density relationships and exit queuing models. A similar approach is used in TransModeler.

Table 11 – Mesoscopic Simulation Tools

Model	Latest Release	Date	Developer	Information Website / Reference
DynaMIT	--	2010	Massachusetts Institute of Technology	http://mit.edu/its/dynamit.html
Dynasmart-P	1.3.0	02/2007	University of Texas at Austin / University of Maryland	http://www.fhwa.dot.gov/research/deployment/dynasmart.cfm
Dynameq	2.5.2	01/2010	INRO	http://www.inro.ca/en/products/dynameq/index.php
TransModeler	2.6	06/2010	Caliper Corporation	http://www.caliper.com/transmodeler/default.htm
AIMSUN	7.0	11/2011	Transport Simulation Systems (TSS)	http://www.aimsun.com/wp/?page_id=21
CONTRAM	8.3b	12/2008	Mott MacDonald / TRL	http://www.contram.com/
DynusT	3.0.1	04/2011	University of Arizona	http://dynust.net/wikibin/doku.phpm

Information as of June 2012

In CONTRAM, traffic is again modeled as small groups of vehicles, called packets. While each packet is independently assigned a route, travel times on individual roadway links are determined by the number of packets present on the link and macroscopic speed-density relationships.

In DYNAMEQ, the traffic simulation model simply predicts the time at which each vehicle is expected to exit its current link, and from which lane this exit will be made. Lane selection decisions consider a vehicle's intended path downstream of his current position, the lane(s) that may be used to execute the next turning movement, and the prevailing traffic conditions on each lane between the vehicle and the end of the link.

DynusT is an open-source dynamic traffic simulation and assignment tool being developed by the University of Arizona to support regional operational planning analysis. This model is more specifically being developed to promote the use of advanced modeling theories and techniques in transportation policy decision making. While relatively recent, it model has already been used to evaluate the network impacts of freeway corridor improvements, integrated corridor management strategies, as well as to assess the effectiveness of evacuation plans and work-zone management plans.

A mesoscopic modeling approach was finally recently introduced into the AIMSUN software. This model features an event-based simulation approach in which time progresses from one event to the next, and thus not at constant intervals. This model still simulates the movements of individual vehicles, but uses aggregate rules to replicate their behavior. Simplified car-following and lane-changing models are used to determine the time taken by individual vehicles to travel along road sections. At the end of each section, gap-acceptance rules are used to determine when a vehicle can enter the node linking the current roadway section to the next one along the path of the vehicle. The mesoscopic simulator was first introduced in Version 6 of AIMSUN. In this version, the microscopic and mesoscopic modeling approaches could not be used to model different sections of the same network. This constraint was removed with the release of Version 7 of AIMSUN in November 2011.

3.1.4. HYBRID MODELS

The use of simulation models combining microscopic, mesoscopic and macroscopic approaches has been the subject of many academic research projects. The main idea behind hybrid simulation frameworks is to take advantage of the strength offered by each modeling approach. Within a hybrid framework, a microscopic model can conceptually be used to provide a detailed simulation of traffic movements within an area of interest, while a mesoscopic model can be used to provide a coarser simulation of traffic movements outside the area of interest. An example of hybrid modeling from the US-101 CSMP corridor in Santa Barbara and Ventura is shown in Figure 6. Another example involving AIMSUN is shown in Figure 7. In the first example, the freeway mainline and ramps are modeled microscopically, while surrounding arterials are modeled mesoscopically. In the second example, a set of links at the center of the area of interest are modeled microscopically, while the surrounding links are modeled mesoscopically.

Reasons frequently invoked for using hybrid modeling approaches include an ability to model much larger networks than possible with microscopic models, but with greater details than macroscopic models. The ability to model large networks using different fidelity levels reportedly further allows for a better capture of boundary effects at the edge of an area of interest, the evaluation of impacts of proposed network improvements on traffic outside the area of interest, and an improved ability to simulate route diversion and choice effects on a network scale.

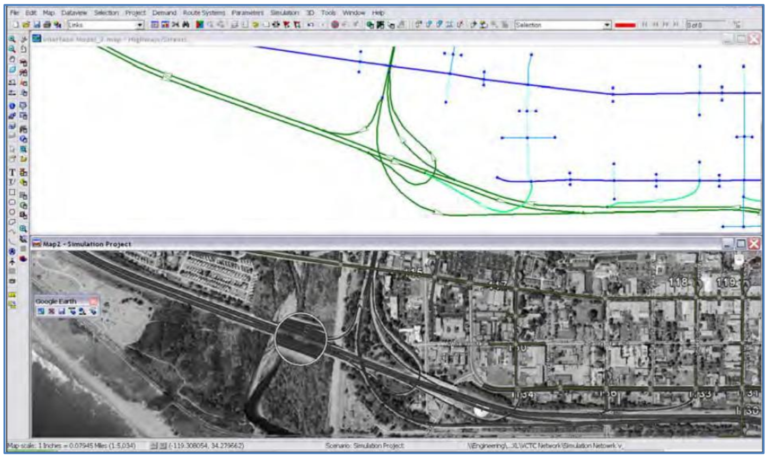


Figure 6 – TransModeler Hybrid Modeling Example (US-101 Santa Barbara/Ventura Corridor)

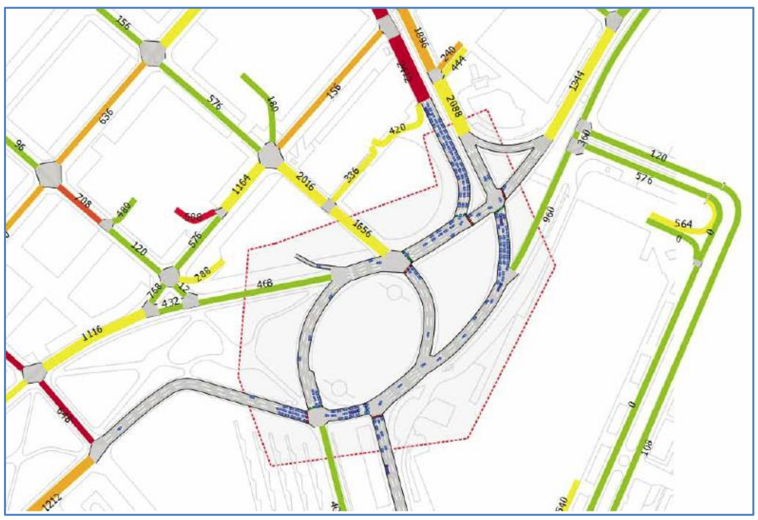


Figure 7 – AIMSUN 7 Hybrid Modeling Example

Hybrid modeling capabilities are currently primarily being offered by TransModeler and AIMSUN. TransModeler was the first commercial model to allow road networks to be developed by intermixing microscopically-defined links with mesoscopic links. AIMSUN added a similar modeling capability with the release of its Version 7 in November 2011. Interested readers can find more information about the hybrid framework that was developed for AIMSUN in Villaro, Torday and Gerodimos (2010).

Despite the recent interest in hybrid modeling, there are still uncertainties regarding the ability to effectively utilize such an approach to evaluate traffic operations in large networks. Attempt to utilize hybrid models for evaluating improvements along the I-5 North Coast and I-805 corridors in San Diego were eventually abandoned due to difficulties in obtaining a calibrated model. Some concerns have also been issued regarding the behavior of vehicles on links at the boundary between the microscopic and mesoscopic areas, as well as the ability to adequately replicate route selection for paths including links in both the microscopic and mesoscopic areas. While some difficulties have been encountered, these may have been linked to the novelty of the adopted modeling approach. Changes that have been made within the simulators since then may have solved or lessened some of the encountered problems. Therefore, this simulation approach may still warrant some careful evaluation before being adopted on a large-scale basis for conducting corridor evaluations.

3.2. TRAVEL DEMAND MODELS

Travel forecasting models have traditionally employed a four-step sequential process to predict the number of trips expected to be made within a network. These four steps are:

- **Trip generation and attraction –** Estimation of the number of trips produced from each zone and number of trips attracted to each zone based on the socio-demographic characteristics of the zone. Trips are usually produced for very specific purposes, such as home-based work trips, home-based non-work trips, and non-home-based trips.
- **Trip distribution –** Determination of the spatial distribution of trips between travel zones, i.e., the assignment of destination zones to trips generated from a particular zone.
- **Mode choice –** Determination of the proportion of trips between each O-D pair that are made by car, transit, and other available transportation modes.
- **Trip assignment –** Allocation of trips made between each pair of origin and destination zones to specific routes within a transportation network based on parameters such as distance, speed, time, perceived cost, and roadway capacity.

Traditional models base trip generation, trip distribution, and mode choice decisions on the average socioeconomic and land-use characteristics of each defined travel zone. In more advanced models, trip forecasts also consider characteristics of the transportation network, such as tolls, parking costs, roadway capacity, or transit availability. Joint effects may further be considered through feedback loops between the steps.

In recent years, in response to the realization that traditional four-step forecasting models do not necessarily reflect the inherent complexity of travel decisions, there has been growing interest in using activity-based models to forecast travel patterns. In an activity based model, travel is derived from participation in activities and depends on the organization of those activities. The socioeconomic characteristics of individual households are used to estimate household interactions and produce travel patterns for each individual. In contrast to traditional four-step models, which use discrete trips as the standard travel unit, activity-based models analyze travel in sets of trips called tours. Tours may include a single trip or multiple trips chained together. This approach allows modeling the effects that coordinated decisions may have in determining when and where trips occur. To create tours, activity-based models typically synthesize a set of persons and households that are distributed based on the socio-economic and demographic characteristics of the area. Desired trip patterns are then generated by considering the travel needs and constraints of each individual. These desired trip patterns are then used to identify primary and secondary travel destinations and, finally, to establish tours.

Table 12 lists the commercial travel demand forecasting models that were commonly used by transportation planning agencies at the time of the study. Among these, TransCAD can be considered as the dominant model. However, CUBE, EMME and VISUM also enjoy relative widespread utilization. VISUM, in particular, is a travel demand model that is being sold as a companion to the VISSIM microscopic traffic simulator. Other occasionally cited models include Transims, QRS II, TRANPLAN and TP+. The last two are legacy models that are no longer under development and which are, in many cases, in the process of being replaced by other models. Some agencies also use their own travel demand forecasting models.

Table 12 – Commercial Travel Demand Forecast Models

Model	Forecasting Approach	Latest Release	Release Date	Developer	Information Website / Reference
TransCAD	Traditional four-step	5.3	11/2009	Caliper Corporation	http://www.caliper.com/tcovu.htm
EMME	Traditional four-step	3.4.1	12/2010	INRO	http://www.inro.ca/en/products/emme/index.php
CUBE	Traditional four-step / activity-based	6.0	11/2011	Citilabs	http://www.citilabs.com/products/cube
VISUM	Traditional four-step / activity-based	12.0	11/2011	PTV AG	http://www.ptvag.com/software/transportation-planning-traffic-engineering/software-system-solutions/visum/
Transims	Activity-based	4.0.8	01/2011	Los Alamos National Laboratory – Now open-source model	http://code.google.com/p/transims/
QRS II	Traditional four-step / activity-based	8.2	03/2011	AJH Associates	http://my.execpc.com/~ajh/

While there is a growing interest in using activity-based models, the vast majority of transportation planning agencies still use models based on the traditional four-step forecasting method. While various activity-based models have been developed by university research groups, applications of these models beyond demonstration projects remain relatively limited. An example of an activity-based model currently in use is the San Francisco Chained Activity Modeling Process (SF-CHAMP), a travel demand model that has been developed by the San Francisco County Transportation Authority. Another example is SimAgent, a model currently being developed by the University of California at Santa Barbara, the University of Texas at Austin and the Arizona State University for the Southern California Association of Government (SCAG).

3.3. INTEGRATED MODELING SUITES

There is significant interest in developing evaluation tools that would integrate travel demand models with traffic simulation models. Such linkages are generally proposed to overcome limitations associated with specific models and to improve overall transportation system modeling capabilities. Three types of linkages are generally considered:

- Planning models feeding data into a network traffic simulation tool – Here, demand data or trip tables are fed into the traffic simulator to perform time-dependent traffic assignments.
- Simulation models feeding data into planning models – This approach seeks to utilize the detailed performance measures generated by a traffic simulation model to refine the network speeds or enhance the travel times used within the travel demand model.
- Planning models dynamically interacting with network traffic simulation tool - This approach includes an iterative feedback loop between the traffic simulator and travel demand model to generate over time an equilibrated behavioral result.

In recent years, many simulation packages have introduced functions allowing them to import data from common travel demand forecasting software, such as TransCAD or EMME, intro traffic simulation models. Integration efforts have been pursued by software developers offering both a traffic simulator and a travel demand forecast model (for instance, VISUM/VISSIM from PTV AG and TransCAD/TransModeler from Caliper). However, these developments remain strictly unidirectional. There is still no commercial software enabling outputs from traffic simulation models to be directly passed back to a travel forecast model. While possible, such linkage must typically been developed by the model users themselves using Application Programming Interfaces (APIs).

3.4. TRAFFIC SIMULATION PROCESSES

Most traffic simulation models use a similar framework to simulate the behavior of vehicles within a road network. Key elements of this framework include (Dowling, Holland and Huang, 2002):

- Modeling of time progression;
- Randomization of simulation elements;
- Traffic demand modeling;
- Vehicle generation process;
- Path selection within a network;
- Vehicle behavioral rules along links; and
- Vehicle behavioral rules at intersections.

Each of these elements is briefly reviewed in the subsections that follow.

3.4.1. SIMULATION TIME STEPS

Traffic simulation models usually implement a discrete-time process, i.e., a process in which time advances at fixed intervals. This can be contrasted to discrete-event processes, in which time advances at variable intervals from one event to the next. In most models, the position, velocity and acceleration level of each vehicle is reevaluated once every time step to reflect changes that may have occurred in the last time step. While earlier models typically advanced time using 1 s increments, most current commercial models utilize a default time step of 0.1 s. Some models even allow using intervals as short as 0.01 s to model particularly complex situations.

Using short time steps allows models to replicate observed traffic behavior more precisely by providing drivers more opportunities to respond to changing traffic conditions. This has particularly significant consequences on the ability to replicate fast-moving flows. For instance, consider a vehicle traveling at 60 mph. When using a 1-s time step, the shortest reaction time that can be considered is 1 s. In this situation, a vehicle would travel a minimum of 88 ft, or approximately 5 car lengths, before starting to respond to changing traffic conditions. This could result in overreactions, such as harsh acceleration and deceleration, to counterbalance the long reaction time. With a 0.1 s time step, a response could instead occur as soon as the vehicle travels 8.8 ft, depending on the model’s setup for driver reaction time.

Short time steps also enable simulation models to better replicate the operation of traffic detectors. This has important significance for the modeling of ITS applications. Short, fast-moving vehicles can, for instance, pass over a short loop detector within a second. Unless the simulation software can deduce that a vehicle has crossed a detector between time steps (some software will only detect a vehicle if it is actually present above the detector at the end of a time step), using a 1-s time step can result in some vehicles being undetected, and thus inaccurate monitoring of traffic flows.

While short time steps allow for more refined simulations, they also increase computational load and the time needed to execute simulations. Ideally, the time step used should reflect a balance between simulation needs and simulation time requirements. For instance, a point may be reached where increases in simulation time may not be justified by the marginal improvements in model accuracy obtained from using smaller time steps. It is also possible to go too far in the search for precision. For instance, some driver behavior models require knowledge of historical conditions (for instance, the speed of the lead vehicle during the past few time steps) to assess drivers' reactions. In some models, the use of very short time steps could further reduce the ability to effectively consider past behavior or lead to the application of behavioral models outside their intended validity range.

3.4.2. STOCHASTIC EFFECTS

To replicate the range of observed driving behaviors, random variables are commonly used to introduce stochastic variability in simulation processes and to produce a plausible range of responses. For instance, random variable sampling if often used to determine whether each newly generated vehicle will be controlled by a passive, moderate or aggressive driver. This aggressiveness level can in turn affect the desired speed at which each driver will seek to travel, the headway maintained with the vehicle ahead, or the minimum gap accepted when trying to cross or merge into a traffic stream.

Random processes are typically generated through the use of a random number generator. This requires that a starting number, or "seed", be provided for the random sequence. Most models have a default seed and offer the option to change it. The latter option is important, as simulation runs executed with the same seed, same computer, and same network will usually produce identical outputs. In most cases, the random variables are assumed to be normally distributed. While this assumption may adequately replicate the observed variability of certain parameters, there has been some concerns that it may not adequately represent other parameters. There are also concerns that the stochasticity offered by commercial simulation models may be lower than the real-world variability.

As a result of a model's stochasticity, multiple simulation runs using different random number seeds are typically required to conduct proper evaluations. The exact number of simulation runs that must be executed will depend on the variability of traffic conditions within the simulated network. Networks that are sensitive to slight variations in operational control or geometry will usually require more runs than networks with less sensitive traffic behavior.

3.4.3. MODELING OF ORIGIN-DESTINATION FLOWS

Traffic demand within simulation models is typically defined using one of the following two approaches:

1. **Link flow rates and turning percentages –** This approach requires specifying the flow of vehicles occurring on each roadway link. This is often done by specifying the flow rates at the network entry points and turn proportions at each intersection or junction.
2. **O-D flow matrices –** This approach requires the development of a matrix containing the average vehicle flow rate between each possible pair of origin and destination nodes. At each origin, the total number of vehicles to be released onto the network corresponds to the summation of all the specified outgoing flow rates from the node. The destination of each newly released vehicle

is then randomly assigned based upon the proportion of vehicles traveling to each possible destination. In this case, the path followed by each vehicle onto the network is subsequently determined using a minimum-cost search algorithm.

The main difference between the two modeling approaches described above is the ability to respond to changes in traffic conditions. In the first approach, the flow rates and turn proportion are fixed. The traffic demand modeling is therefore not affected by changes in traffic conditions. In the second approach, the flow supported by each link is indirectly determined since it is simply the summation of all the O-D flows having the link along their minimum path. This modeling approach thus allows for changes in traffic demand to be reflected in the network behavior.

3.4.4. VEHICLE GENERATION PROCESS

During every time step, simulation models typically determine how many vehicles should be released onto a road network within the time step. Vehicles may be released from a specific entry link or a zone from which multiple entry links can be used. At each entry point, vehicles may further be released following either a uniform or random process. In a uniform process, vehicles are released at a fixed interval corresponding to a defined average hourly flow rate. In a random process, the interval between vehicles is allowed to vary around a mean value that corresponds to the defined average flow rate.

Random release processes do not guarantee that the total number of vehicles released onto a network over a given period will match the specified average flow rate. Some runs may generate more vehicles than others. To reduce the likelihood of producing runs with noticeably different numbers of released vehicles, some simulators offer the option to force the generation process to produce a number of vehicles matching exactly the defined average flow rate over the simulation period. This is done by periodically adjusting the mean rate at which vehicles are released to ensure that the target number of vehicles is reached. However, a potential consequence of this option is that it may produce simulations featuring less stochasticity.

In addition to determining the release schedule of vehicles, the vehicle generation process is also responsible for assigning the characteristics of each vehicle, such as length, weight, height, engine power, maximum speed, and acceleration/deceleration capabilities. The aggressiveness and awareness of surrounding conditions of individual drivers are also determined by this process. Similar to the process for releasing vehicles, vehicle and driver characteristics are often determined using a random sampling process. Within this process, vehicle characteristics are typically assigned based on a distribution of vehicle types provided by the modeler, while driver characteristics are frequently assigned based on user-defined proportions of drivers who are familiar (commuters) and unfamiliar (non-commuters) with the modeled road network.

3.4.5. PATH SELECTION

In models specifying the traffic demand through an O-D flow matrix, vehicles released from a given origin are randomly assigned a destination based on the proportions of trips assigned to each possible destination. The path followed by a vehicle to reach its assigned destination is then determined based on a minimum cost path search algorithm that may consider travel distance, travel time, out-of-pocket costs such as tolls, or a weighed combination of these parameters. Perturbation factors may also be used to introduce randomness in the travel cost estimates and allow the path selection to reflect the fact that travelers often do not have a perfect knowledge of traffic conditions. Depending on the model, the identified path may be fixed or allowed to dynamically change as a vehicle progresses through a network in response to new traffic conditions. While the latter option conceptually allows replicating the possibility that real-world motorists may alter their initially intended route, this process also greatly increases the computational burden and the level of effort required to calibrate a model.

In models not using an O-D matrix, no path is assigned to individual vehicles. A vehicle's ultimate destination is determined by the turn decisions made at each decision point. Most models within this category require the modeler to define turn percentages at nodes where multiple outgoing paths exist. Whether a vehicle approaching the node will go straight, turn right or turn left is then determined by a random process. Here, the path followed by a vehicle through a network is simply a reflection of the various turning decisions that were made at each node. A notable consequence of this approach is the possibility that individual vehicles may drive in circles within the network.

3.4.6. BEHAVIOR ALONG LINKS

Links typically represent sections of street where the road geometry and demand are relatively constant. They can be viewed as one-directional pipes through which vehicles enter from one end and exit from the other. Four basic sets of behavioral rules are used by microscopic models to govern the movements of vehicles along a link:

- **Lead-vehicle behavior –** Lead-vehicle models characterize the longitudinal movement of a vehicle when its progression is not affected by other vehicles ahead. They determine the desired speed of a vehicle, which is usually a function of the link's defined free-flow speed and the driver's aggressiveness level. More aggressive drivers are allowed to travel faster than the free-flow speed, while less aggressive drivers typically travel at slower speeds. Speed reductions may also be implemented in response to tight curves or other geometrical elements.
- **Car-following behavior –** Car-following models characterize the longitudinal movement of a vehicle when other vehicles ahead affect its progression. These models attempt to move a vehicle forward at a desired speed while maintaining a safe distance from the vehicle immediately ahead. More advanced models also consider vehicles further ahead and those in adjacent lanes. In most cases, a target mean headway is used to determine the distance a vehicle should maintain with the vehicle(s) ahead and the speed it is allowed to travel when approaching other vehicles. Variations in driver aggressiveness and vehicle characteristics will again result in slightly different behavior from one vehicle to the next. In virtually all models, the rules are set so that no vehicle will collide with another vehicle or object.
- **Lane-changing / lane selection models –** Lane-changing models attempt to replicate the rationale used by drivers to select a particular lane for travel and the process that is followed to perform lane changes. These models typically require that an acceptable gap be available in the adjacent lane. In most models, a distinction is made between mandatory, discretionary and anticipatory lane changes. Mandatory changes are made when the road geometry dictates the change, such as the need to move into a designated turning lane. Discretionary changes are made to pass slower vehicles. The probability of a vehicle making a discretionary lane change is usually a function of the difference in speed between the two vehicles and the available gaps between vehicles in the adjacent lane. Anticipatory lane changes are finally made to pre-position a vehicle for an upcoming turn or to avoid slower vehicles entering a freeway from an on-ramp. These lane changes are typically modeled by defining the location where motorists become aware of a situation that may warrant a lane change. Depending on the model, this

distance may be defined as a number of roadway links that a driver can look ahead, a preset distance, or a distance that is a function of the speed of the vehicle.

- **Special situations –** In addition to the above three sets of rules, many models will also custom behavioral rules for better replicating observed vehicle behavior a specific locations, such as at freeway merges, where travelers may receive information from dynamic message signs, etc.

3.4.7. BEHAVIOR AT INTERSECTIONS

Two primary sets of behavior rules determine the movement of vehicles at intersections:

- **Gap acceptance models –** Gap acceptance models are used to replicate the process by which drivers determine when it is safe to change lanes and cross or merge into a stream of vehicles. In most models, movements at intersections are ranked according to predefined priority levels. Lower priority vehicles will yield passage to higher priority vehicles and only enter an intersection if there is a sufficient gap between two successive vehicles. Depending on the model, the critical gap may be either a fixed or customizable value.
- **Speed control –** Most simulation models will impose speed reductions for vehicles making turns within an intersection. The speed reduction may be a fixed value based on the type of turn being made or calculated based on the radius and angle of the turn.

In many models, there is no crosscheck to ensure that realistic vehicle movements occur within an intersection. After a vehicle has been allowed to enter an intersection, it will typically behave as if no other traffic exists, except for the vehicles ahead on its destination link. This will often lead to situations in which two vehicles are shown onscreen as occupying the same space. To avoid such situations, some models have recently introduced spatial awareness logic within their simulation process. As an example, this is the case of both Paramics and AIMSUN.

3.5. DATA REQUIREMENTS

Microscopic simulation models typically require more data than other types of models. The required data can typically be grouped into the following categories:

- **Network geometry** – Data describing various geometrical aspects of the study corridor, such as the location of intersections, road widths and curvatures, grades, the number of lanes on each segment, equipment used for monitoring traffic performance, etc.
- **Travel demand** – Data characterizing fleet composition and the distribution of flows between the various origin and destination nodes. Rules followed by travelers to select a path within a network may also be included in this category.
- **Traffic control** – Data characterizing the operation of traffic signals and ramp meters, priority schemes for transit vehicles at signalized intersections, etc.
- **Network performance/calibration –** Data characterizing how traffic behaves along roadway elements, such as volumes, speeds, travel times, location of bottlenecks, etc.

Two major factors often drive data requirements: developing an accurate representation of existing network elements and ensuring that simulated flows replicate observed behavior. The modeling of network geometry is relatively straightforward since this process generally focuses on fixed and well defined elements. While traffic signal operations may include some variable elements, such as vehicle-actuated control or automated plan selection based on observed traffic flow levels, these elements can often be quantified and adequately modeled. The modeling and calibration of traffic flows and driver behavior usually imposes more complex data collection needs as traffic flows continuously fluctuate and driver behavior is affected by various environmental factors. In many cases, observations from a single day may not be sufficient to adequately characterize traffic flows and typical driver behavior.

Table 13 – Typical Data Requirements for Traffic Simulation Models

Category	Data Item	Data sources
Network geometry	• Road network outline • Road types • Length of roadway sections • Roadway curvatures • Roadway width • Number of lanes • Queue storage length	• Construction drawing • Images from Caltrans Digital Highway Inventory Photography Program(DHIPP) • Images from online sources (e.g., Google Maps) • Geographical Information System (GIS) files • Field surveys
	• Intersection geometry and channelization	• As-built drawing files • Field verification
	• HOV ingress/egress locations • On- and off- ramp locations • Lane drop and lane gain locations	• Postmile book • Aerial images • Photo logs
	• Elevation data	• As-built drawing files • field survey using GPS devices • Online sources (Google Maps, etc.)
	• Location of traffic surveillance detectors	• As-built drawing files • Metadata from traffic monitoring systems • Online sources (Google Maps, etc.) • Field surveys
	• Lane assignments	• As-built drawing files • Online sources (Google Maps, etc.) • Field surveys
	• Speed limits • Free-flow speeds	• Traffic sources • Field surveys using radar guns • Online sources (Google Maps, etc.)
Travel demand modeling	• Network entry volumes • O-D flow patterns • Travel demand growth	• Regional travel demand model • Field O-D surveys • Traffic counts
	• Turning volumes/percentages • Lane utilization	• Field surveys
	• Transit services	• Bus/train schedules
	• Pedestrian/bicycle flows	• Field surveys
	• Fleet composition • Truck volumes /percentage	• Weight-in-motion data • Traffic sensors with classification capabilities • Field surveys • Statistics from Department of Transportation
Traffic control	• Signal timing plans	• Agency operating the traffic signal (Caltrans, counties or city traffic departments)
	• Ramp metering control plans	• Caltrans data
	• Location of detectors for signal control and ramp metering	• Online sources (Google Maps, etc.) • Metadata from traffic monitoring systems • Field surveys • As-built drawing files
	• Priority control plans	• Online sources (Google Maps, etc.) • Field visit

Table 13 – Typical Data Requirements for Traffic Simulation Models (cont'd)

Category	Data Item	Data sources
Network performance / calibration	• Link volumes • Cordon flows • Average link speeds • Speed distributions	• Traffic sensor data • Field surveys • Traveler information (511) systems
	• Turning volumes	• Data from traffic control sensors • Manual traffic counts • Count cards • Video data processing (Miovision)
Network performance / calibration	• Link travel times	• Traffic sensor data • Probe vehicle runs • Traveler information (511) systems • Data from private surveillance networks (e.g., Traffic.com) • Congestion reports (HICOMP, MPR, etc.)
	• Traffic flow fundamental curve	• Traffic sensor data • Field surveys
	• Location of bottlenecks	• Congestion reports (HICOMP, MPR, etc.) • Traffic sensors • Floating car runs • Field surveys • Aerial photographs
	• Driver behavior parameters	• Traffic sensor data • Field surveys
	• Vehicle characteristics	• Caltrans data • Federal Highway Administration (FHWA) • Car manufacturer data (*adjusted to remove test track factors*) • Online sources • Model defaults

Table 13 lists data typically required by traffic simulation models. While differences in data requirements can be expected between the microscopic, mesoscopic and macroscopic modeling approaches, relatively small variations should be expected among models within a specific approach. Microscopic models typically require the most data due to their need to model individual vehicle behavior in details. Mesoscopic models may require slightly fewer data depending on the simplifications made in their driver behavior models. Macroscopic models typically require the least amount of data, as traffic behavior is usually only characterized by flow rates, average observed speeds, and observed link densities. Table 14 further provides a rough summary of the applicability of simulation models with respect to data quality and fidelity that was developed by Sbayti & Roden (2010) based on a web survey, interviews, and comments from professional modelers.

Table 14 – Applicability of Modeling Approach Given Data Quality and Fidelity

Decision Criteria	Criteria Value Options	Model Applicability		
		Macroscopic	Mesoscopic	Microscopic
Data Quality	Consistent and balanced	Yes	Yes	Yes
	In-between	Yes	Yes	Maybe
	Needs reconciling and balancing	Yes	Maybe	Rarely
Data Fidelity	< 15 minutes	Rarely	Yes	Yes
	15 minutes to 1 hour	Maybe	Yes	Maybe
	> 1 hour	Yes	Maybe	Rarely

Three important documents providing guidance on data collection needs for the development of traffic simulation models relevant to corridor evaluations are:

- *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Simulation Modeling Software* (Dowling, Skabardonis and Alexiadis, 2004);
- *California Department of Transportation Guidelines for Applying Traffic Microsimulation Modeling Software* (Dowling, Holland and Huang, 2002); and
- *Data Framework for Freeway Corridor Performance Evaluation* (System Metrics Group *et al.*, 2010).

The last document is perhaps the most important as it was developed by consulting firms that actively participated in CSMP traffic simulation modeling efforts. This document is based on their experiences in modeling transportation corridors around Sacramento, San Diego, Los Angeles, San Bernardino County and Orange County. Experiences from an earlier demonstration CSMP project led by the California Center for Innovative Transportation (CCIT) along the I-880 corridor in Oakland were also considered (West, 2010). However, the other documents are also relevant based on their frequent citation by reports detailing traffic simulation studies.

3.6. CALIBRATION NEEDS

Calibration involves the adjustment of model parameters to allow the replication of observed, real-world operational conditions as closely as possible. This is a necessary step as no simulation model can be expected to model all traffic conditions with equal accuracy. it can be particularly time demanding since it may involve the review and adjustment of a large set of parameters, each of which can potentially impact the simulating results in a manner highly correlated with other parameters.

Commonly cited references for calibration are the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Microsimulation Models* and the *California Department of Transportation Guidelines for Applying Traffic Microsimulation Modeling Software* documents that were mentioned in Section 3.5. Since both documents share many common contributing individuals, they essentially present a similar calibration process framework.

Calibration typically starts with a model that reasonably replicates the existing roadway network and a set of O-D matrices that have been estimated from observed traffic counts or obtained from regional travel demand models. Various models parameters are then adjusted to bring the simulated behavior and network performance as close as possible to reality. During this process, car following, lane changing and route choice parameters may be adjusted. The most commonly suggested process to execute a model calibration is illustrated in Figure 8 and consists of the following three steps:

- **Calibration of capacity parameters** – An initial calibration is performed to identify the parameters that best reproduce observed link capacities. An adjustment of global parameters affecting behavior across a network is typically performed first, followed by an adjustment of parameters affecting conditions on individual link or at specific intersections. For software also allowing adjustments based on link category, the approach would be to adjust the global parameters first, followed by the categorical parameters and then the local parameters.
- **Calibration of flow volumes and route choice parameters** – This step is only executed for models in which vehicles can take multiple routes to reach a specific destination. Its objective is to ensure that the route choice process adequately replicate observed behavior. Similar to the

previous step, an adjustment of global parameters is often performed first, followed by the adjustment of local parameters.

- **Calibration of system performance** – The final step compares network-wide travel time and queue measurements against field data to ensure replication of overall network performance.

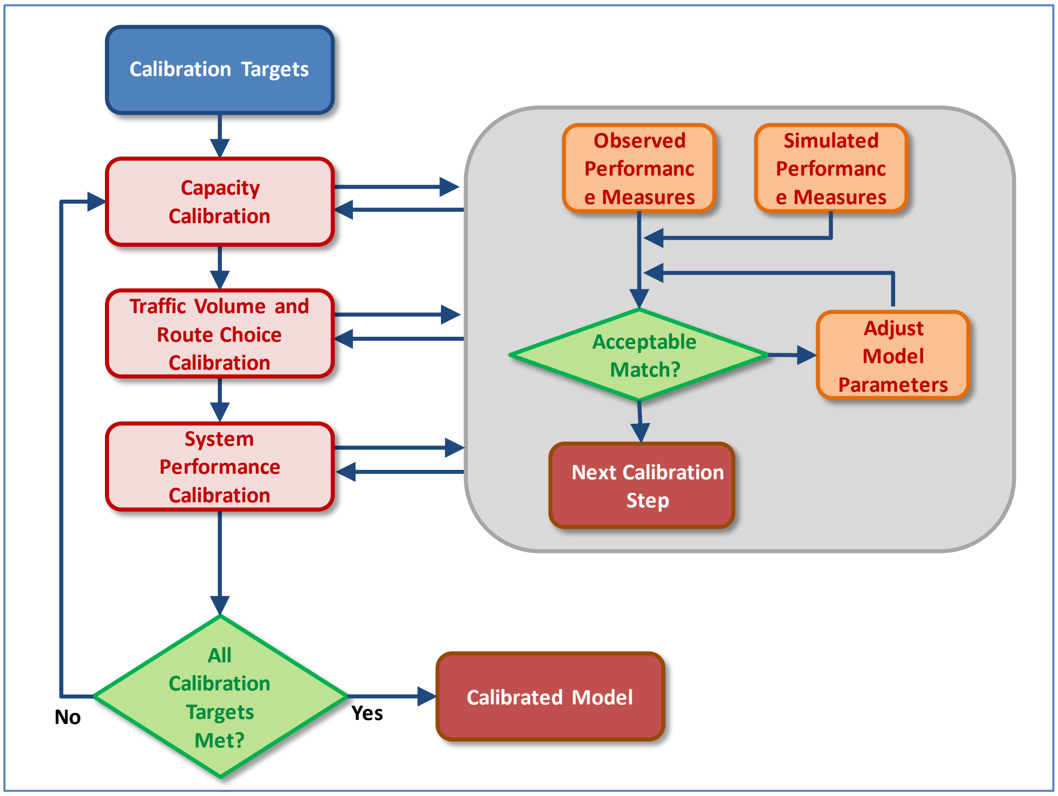


Figure 8 – General Calibration Approach
(Adapted from I-15 ICM Documents produced by TSS)

Table 15 lists calibration targets that are commonly cited in simulation projects. These targets are based on guidelines that were originally proposed by the Wisconsin Department of Transportation for the modeling of Milwaukee's freeway system and which were themselves based upon earlier guidelines from the United Kingdom (Holm *et al.*, 2007). It should be noted that the Wisconsin guidelines at the origin of the calibration targets of Table 15 are currently being updated to address various gaps, such as to replace the "to analyst's satisfaction" items with more objective criteria, to add criteria for turn volumes at intersections, and to add provisions for allowing link volumes to be balanced prior to performing the calibration tests (for the latest information on these revisions, see http://wisdot.info/microsimulation/index.php?title=Model_Calibration).

The widespread use of the targets shown in Table 15 can, to a great extent, be linked to their inclusion in the two documents cited above outlining guidelines for the application of microscopic simulation tools. However, neither document formally imposes the utilized of the listed calibration targets. The targets are provided only as examples of suggested calibration stopping points. Different calibration targets can thus be used if requested by the agency commissioning the simulation work or if warranted by local modeling needs.

Table 15 – FHWA Freeway Model Calibration Criteria

Measure	Calibration Criteria	Acceptance Target
Modeled vs. observed link flows	**Individual link flows:** • Flow within 100 vph for links with flow < 700 vph • Flow within 15% for links with flow between 700 and 2700 vph • Flow within 400 vph for links with flow > 2700 vph • GEH statistic < 5 **Sum of all link flows:** • Flow within 5% • GEH < 4	> 85% of cases > 85% of cases > 85% of cases > 85% of cases For all link counts For all link flows
Modeled vs. observed travel Times	**Journey times within network:** • Within 15% or 1 minute, whichever criterion is higher	> 85% of cases
Visual Audits	**Individual link speeds:** • Visually acceptable speed-flow relationships **Bottlenecks:** • Visually acceptable queuing	To analyst's satisfaction To analyst's satisfaction

In the table, the GEH statistics is a standardized comparison measure that is calculated as follows:

$$\boldsymbol{GEH} = \sqrt{\frac{(\boldsymbol{E}-\boldsymbol{V})^2}{\boldsymbol{0.5}\,(\boldsymbol{E}+\boldsymbol{V})}}$$

Where: E = Model estimated volumes
V = Field counts

The GEH is a modified Chi-squared statistic. It is an empirical formula that was proposed by Geoffrey E. Havers in the 1970s to avoid some of the pitfalls that occur when using simple percentages to compare sets of volumes that may exhibit a wide range of variability. Because the GEH statistic is self-scaling, For instance, the statistic allows using a single test to perform comparisons between high-volume and low-volumes road segments, such as freeway segments carrying over 6000 vph and low-volume ramps only carrying 600 vph.

Data commonly used for model calibration include traffic counts, link travel times, link capacity, and queue statistics. In California, these data could be obtained from PeMS stations, HICOMP reports (for modeling conditions prior to 2009), Mobility Performance Reports, regional 511 systems, field surveys, and private traveler information systems. Ideally, all the required data should be collected simultaneously to avoid using data representative of different situations. However, this is generally not possible. Consequently, data collected for the same period over different days are typically used for modeling purposes. To avoid calibration problems, it is therefore important to establish a consistent process for combining and smoothing data from different days and sources.

3.7. REQUIRED NUMBER OF RUNS TO EVALUATE SCENARIOS

While deterministic simulation models allow network evaluations to be made on the basis of single simulation runs, the determination of average traffic conditions within stochastic models generally requires that multiple simulation runs be conducted using different random number seeds.

The correct theoretical formula for estimating sample size when the variance of traffic conditions within a modeled network is not initially known is given by the equation below:

$$N = \left(t_{\propto/2\,,n-1}\ \cdot \frac{\sigma}{\mu \cdot e}\right)^2$$

Where: $t_{\alpha,\, n\text{-}1}$ = t-statistic from Student's distribution for confidence level α (two-tailed test) and *n-1* degree of freedom;
- α = Confidence level (for instance, 5%);
- N = Total number of runs to be made;
- μ = Mean of performance measure of interest;
- σ = Standard deviation of performance measure of interest; and
- e = Allowable error, specified as a fraction (for instance, 5% as 0.05).

The above equation estimates the number of runs to be executed based on the mean and standard deviation of the performance metric of interest, which can be travel time, delay or any other parameter. The main difficulty in applying the formula is that it requires an iterative procedure to estimate the final number of runs required since the degree of freedom (*n-1* parameter) associated with the *t* statistic is based on the total number of runs *n* needed to achieve a desired accuracy. Since the mean and standard deviation can change with additional runs, the application of the equation requires continuously reassessing the number of runs needed until the actual number match or exceed the requirement given by the formula. As an example, an initial set of 5 or 10 runs may first be executed to obtain an initial estimate of the mean, standard deviation and number of runs required. If the equation returns a higher number of runs based on thee on observed variability, 1, 2, 5 or 10 additional runs are then executed. The process then repeats until the number of runs that have been executed exceeds what is returned by the equation.

A frequent simplification made by practicing engineers is to use the Normal distribution instead of the Student distribution to estimate the number of runs needed. This substitution removes the need to assess a parameter linked to the total number of runs to be made (the degree of freedom *n*) and allows for a straightforward calculation of the number of runs required. Under this assumption, the above equation transforms into the following:

$$N = \left(Z_{\propto/2}\ \cdot \frac{\sigma}{\mu \cdot e}\right)^2$$

Where: Z_α = Standard normal variation based on confidence level α for a two-tailed test;
- α = Confidence level (for instance, 5%);
- N = Total number of runs to be made;
- μ = Mean of performance measure of interest;
- σ = Standard deviation of performance measure of interest; and
- e = Allowable error, specified as a fraction (for instance, 5% as 0.05).

From a theoretical standpoint, the second equation produces precise results only when the coefficient of variation is known. From a practical standpoint, it has been shown to provide reliable estimates when sample sizes are greater than 30, and reasonable estimates for sample sizes exceeding 20 or 25 observations (NCHRP Report 398, Lomax *et al.*, 1997). For sample sizes less than 20, the equation can understate the sample size by approximately 2 runs. However, given the many assumptions associated with simulation modeling, it is often argued that use of the equation is satisfactory for simulation work. This has led to its somewhat widespread use.

3.8. REPORTING CAPABILITIES

Simulations are often conducted to produce performance measures for assessing and comparing the operational impacts of proposed traffic management strategies or improvement projects. In support of this need, most microscopic and mesoscopic models accumulate statistics on the movements of individual vehicles, as well as on the operational performance of individual links and/or nodes. Similarly, macroscopic models typically accumulate aggregated statistics on flow behavior across individual links. Accumulated performance statistics are then reported back to the user at the end of a simulation.

While each modeling tool may provide its particular set of output parameters, outputs generally provide parameters of high interest to traffic operations engineers and system managers, such as:

- Number of released vehicles;
- Volumes;
- Travel times;
- Travel distances;
- Travel speeds;
- Traffic density;
- Incurred delays;
- Number of stops; and
- Queue length statistics.

Most models offer the ability to compile statistics for individual roadway links and the network as a whole. Additional options may also allow reporting statistics for specific vehicle types, groupings of links, or origin-destination trips. Microscopic and mesoscopic models may further offer the ability to trace the movements of specific vehicles and to compile detailed statistics capturing their behavior.

In most cases, simulation results are outputted into simple text files. Post-processing is therefore commonly required to compile the data in a suitable format. Many state-of-the-art models also offer graphical data representation capabilities that can be used to conduct post-simulation analyses and to generate figures for evaluation reports. As an example, Figure 9 illustrates the hotspot viewing tool

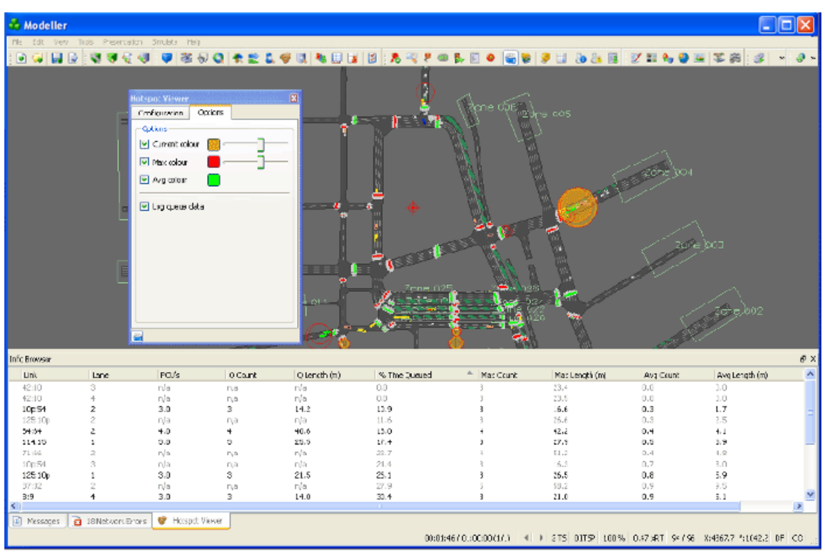


Figure 9 – Congestion Hotspot Viewer Tool in Paramics

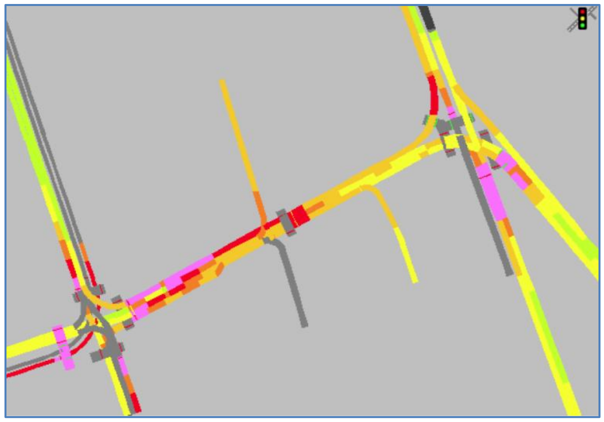


Figure 10 – Speed-Based Link Color Coding in VISSIM

offered by Paramics. The tool allows the user to set up parameters causing circles to be displayed on the screen where queues exceeding a certain size exist, with the radius of the circle linked to the size of the queue. Figure 10 further shows a speed-based link coloring feature offered by VISSIM that can be used to assess operating conditions.

In addition to built-in reporting functions, advanced simulation models often allow additional reporting functionalities to be developed through an application programming interface (API). Models that include such a capability include Paramics, VISSIM and AIMSUN. Depending on the provided programming capabilities, additional functionalities may be developed to allow the collection of vehicle traces (similar to what a GPS device would do), the compilation of vehicle operations statistics (e.g., acceleration noise, stopped delay, percentage of travel above or below certain speeds), or the compilation of statistics on vehicles traveling on specific roadway segments, traversing specific intersections or traveling along specific roads. Some models also allow the development of functions enabling the collection of custom statistics describing the operation of loop detectors, traffic signals, and other traffic control devices.

3.9. COMPARATIVE ASSESSMENT OF MODELING APPROACHES

Table 16 summarizes the main advantages and limitations associated with the microscopic, mesoscopic and macroscopic modeling approaches. This summary is based on comparative evaluations reported in the professional literature (Middleton and Cooner; 1999; Helbing *et al.*, 2002; Naguel *et al.,* 2003; Ratrout and Rahman, 2009), as well as personal experiences of members of the project team.

A key observation is that while microscopic tools generally provide the highest level of detail and greatest potential for modeling complex situations, they also impose much greater input data requirements and more complex calibration processes, particularly for the modeling of large networks and networks involving parallel routes. The extent of these requirements often lead to consider splitting large or long networks into smaller sections that can be modeled separately. Such a split is often possible in networks featuring low-volume areas that can be used a break points. However, not all networks or corridors may necessarily be spit.

On the other side, while macroscopic have reduced data requirements, allow the modeling of large networks, and feature quicker execution speeds, they may not have the capability to adequately model situations in which interactions between individual vehicles significantly affect traffic operations. This may impose limitations on the extent to which these models can be used to evaluate emerging Intelligent Transportation System (ITS) applications. For instance, macroscopic models may have difficulties replicating applications involving specific vehicles responding to specific situations, such as gap-acceptance signal control logic, applications seeking to provide individual motorists with context-specific travel information, or connected-vehicle applications promoting interactions between adjacent vehicles via wireless communications.

Table 16 – Comparative Assessment of Simulation Modeling Approaches

Type	Advantages	Limitations / Disadvantages
Microscopic	• Simulate the behavior of individual vehicles. • Model interactions between individual vehicles. • Model inter-modal interactions. • Can analyze complex operational strategies or situations (e.g., complex intersections, congestion pricing, complex weaving sections). • Ability to model situations where lane behavior is affected by traffic queues on adjacent lanes. • Can simulate complex traffic signal control schemes. • Animations showing the movements of individual vehicles are particularly effective tools for communicating simulation results with policy-makers and the public.	• Considerable input data required to adequately model road networks. • Requires significant attention to data quality and consistency. • Calibration of model parameters can be time consuming and costly. • Computational needs and model complexity creates significant difficulty in simulating large networks. • Certain required parameters, such as specific driver behavioral parameters, are difficult to measure directly. • Modeling parameters are often location-specific and may not be transferable to other locations without adjustments. • Slight changes in coding of roadway elements may result in significant changes in simulation results. • Often requires the creation of smaller origin and destination zones than those provided by travel demand models, creating a need for adjusting the trips forecasted by the demand model. • Significant time required for executing simulations, particularly on low-end computers. • Significant level of expertise required for modeling.
Macroscopic	• Fewer input data than microscopic and mesoscopic models. • Ability to model large networks. • Relatively easy calibration and validation. • Data needed for simulation often available without conversion from DOT databases and regional travel demand models. • Fast simulation execution speeds.	• Individual vehicles not modeled. • Unsuited to analyze problems where effects on vehicle interactions is critical (e.g., complex weaving sections). • Cannot simulate ITS applications targeting specific vehicles. • Limited ability to simulate real-time and adaptive traffic signal control (some modeling possible with short time intervals).
Mesoscopic	• Better representation of individual travel behaviors than macroscopic models. • Relatively easy calibration and validation. • Ability to model large networks. • Relatively fast simulation speeds. • Can be used to perform dynamic traffic assignments on large networks.	• Unsuited to analyze problems where accurate replication of interactions between individual vehicles is importance. • Modeling may be based on heuristic methods, not clearly defined behavioral rules (microscopic models) or traffic theory (macroscopic models). • Can only model approximate signal timing plans.

Mesoscopic simulation models lay conceptually between the microscopic and macroscopic modeling approaches. While their simplified modeling allows for quicker simulation speeds than microscopic models, this simplification does not necessarily come with the benefit of fewer data requirements. Utilization of these models is often still more data-intensive than with macroscopic models. In addition, most of the existing mesoscopic models have not yet been fully tested regarding their ability to evaluate the full range of operational conditions of potential interest to system managers. This is due to the fact that these models have to date been almost exclusively used to evaluate dynamic traffic assignment scenarios.

Based on the above observations, it can only be suggested that the selection of a particular model to use for conducting and operational evaluation should be based on a thorough assessment of the needs of the study and the capabilities of available models. While microscopic models will often offer the most versatile modeling capabilities, the utilization of macroscopic or mesoscopic models can be considered to reduce the cost and duration of a given evaluation project, if available models can provide a suitable modeling alternative.

4. SURVEY OF SIMULATION MODELERS AND DECISION-MAKERS

To assess current attitudes towards utilizing traffic simulation models to evaluate transportation corridors, PATH has conducted a survey of individuals who have been involved in the modeling of transportation corridors or had used simulation results to determine desired improvements along a corridor. While this survey was primarily addressed to individuals who had worked on the development of CSMPs in California, it was also distributed outside California in an attempt to gauge general practice trends.

The following subsections briefly describe the population that was surveyed, the survey questionnaire that was developed, the method of distribution of the survey, and a summary of key observations from the responses received.

4.1. SURVEY POPULATION

Table 17 identifies the organizations from which responses were collected from one or more individuals. The survey primarily targeted individuals based in California who have been involved in the development of CSMPs and who either played a role in the development of a corridor's traffic simulation model or used results from simulations. This pool included staff from various Caltrans Districts and metropolitan planning organizations, as well as individuals working for consulting firms that routinely conduct simulation work for Caltrans.

In addition to the California-based respondents, the survey was also sent to simulation professionals outside California in an attempt to obtain an out-of-state perspective regarding the modeling of large transportation corridors or simulation. Targeted individuals within this pool included staff from various departments of transportation and individuals working from private consulting firms. However, perhaps due to a lack of incentives, very few out-of-state individuals responded to the survey.

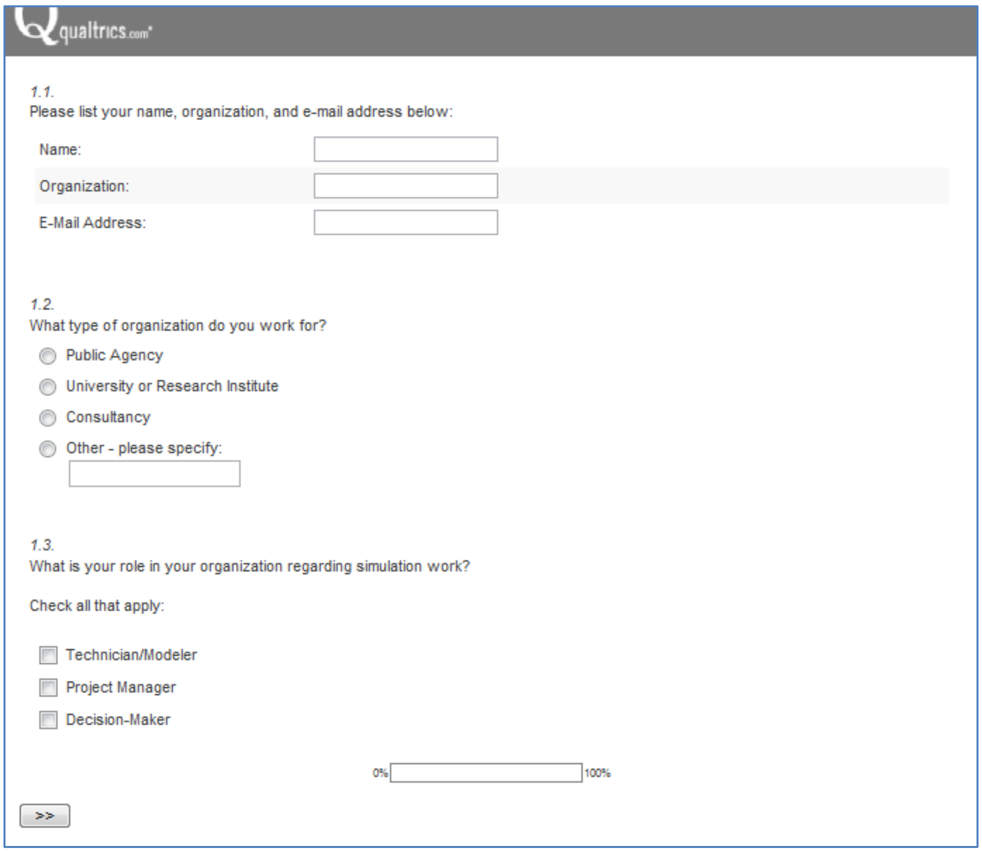
Table 17 – Agencies Responding to the Survey

Category	Agency/Firm/District
Caltrans	• Districts 3, 4, 5, 7, 8, 10, 11, 12
Metropolitan planning organizations	• San Diego Associations of Governments (SANDAG) • Metropolitan Transportation Commission (MTC)
Consulting firms operating in California	• Braidwood Associates • Cambridge Systematics • CH2M Hill • CLR Analytics • DKS Associates • Dowling & Associates (now merged with Kittelson & Associates) • System Metrics Group
Consulting firms operating outside California	• Leftwich Consulting Engineering (Florida)

4.2. SURVEY METHODOLOGY

Individuals invited to participate in the survey were contacted via e-mail and provided a link to the online questionnaire. Each respondent was initially asked to provide responses within a two-week period. If this was not done so, a reminder was then sent via email.

The survey was developed using trial software offered by Qualtrics (http://www.qualtrics.com/), a private company based in Provo, Utah. The software enables users to create and administer their own web-based surveys. It allows for significant survey customization, including response validation, display/skip logic to show/hide questions, branch logic in order to show/hide entire question blocks, etc. Figure 11 below presents a screenshot of how the survey looked to participants.



qualtrics.com

1.1.
Please list your name, organization, and e-mail address below:

Name:

Organization:

E-Mail Address:

1.2.
What type of organization do you work for?

- Public Agency
- University or Research Institute
- Consultancy
- Other - please specify:

1.3.
What is your role in your organization regarding simulation work?

Check all that apply:

- Technician/Modeler
- Project Manager
- Decision-Maker

0% 100%

>>

Figure 11 – Screenshot of Online Survey

4.3. SURVEY QUESTIONNAIRE

Table 18 presents a summary of the various questions that were asked as part of the survey. Three sets of questions were developed, each targeting a specific group of individuals. The first set targeted technicians/modelers (T/M), i.e., individuals directly involved in the development and calibration of simulation models. The second set was directed towards project managers (PM), while the third and final set targeted decision-makers (DM). The questions that were presented to each group are shown in the last three column of each row. While some questions were specific to a given group, others were presented to multiple groups.

Table 18 – Survey Questions

Question		T/M	PM	DM
Identification of Respondent				
1.1	Please list your name, organization, and e-mail address below.	●	●	●
1.2	What type of organization do you work for?	●	●	●
1.3	What is your role in your organization regarding simulation work?	●	●	●
Assessment of Agency's Simulation Experience/Knowledge				
2.1	To what extent has your organization used traffic simulation models for evaluating freeway operational strategies?	●	●	●
2.2	On projects requiring the use of traffic simulation who usually executes the simulation work?	●	●	●
2.3	Which traffic simulation tools have you used recently to conduct a corridor study?	●	●	●
2.4	Any reasons why a particular traffic simulation model is used?	●	●	●
2.5	Which travel demand forecasting model(s) do you or your agency primarily use?	●	●	●
Assessment of Individual's Simulation Experience/Knowledge				
3.1	What types of simulation experience do you have?	●	●	●
3.2	What do you consider your skill level in traffic simulation applications?	●	●	●
3.3	For what purpose do you typically use traffic simulation models?	●	●	●
Description of Project for which Answers Will Be Provided				
4.1	Identification of corridor for which answers are provided.	●	●	●
4.2	What was the level of traffic congestion along the corridor for the base year?	●	●	●
4.3	For what projection horizon were the traffic simulations conducted?	●	●	●
Purpose of Traffic Simulation				
5.1	In this project, for what purpose was traffic simulation used?	●	●	●
Scenario/Model Application				
6.1	Which GEOMETRIC improvement strategies were considered in this project?	●	●	●
6.2	Which TRAFFIC OPERATIONS strategies were considered in this project?	●	●	●
6.3	Which TRAVEL DEMAND MANAGEMENT strategies were considered in this project?	●	●	●
6.4	Which TRANSIT SERVICE improvement strategies were considered in this project?	●	●	●
6.5	Were there any other improvement strategies considered in this project?	●	●	●
Data Collection				
7.1	Which data were used to develop the corridor's base year traffic demand?	●		
7.2	Were agencies from which data were sought supportive of the modeling effort?	●		
7.3	What percentage of time and/or funding was spent collecting data for the simulation modeling?	●		
7.4	Who conducted the data collection?	●		
7.5	Did the following factors limit the data collection efforts?	●		
7.6	Were there any issues with the input data?	●		
7.7	How do you rate the time spent collecting input data for the traffic simulation model?	●		
Model Selection				
8.1	What traffic simulation model(s) was (were) used to conduct the study?	●		
8.2	Are there particular reasons why the selected traffic simulation model(s) was (were) used?	●		
8.3	On a scale of 1 to 10, how important do you rate each of the following factors (specific model features, maturity of tool, purpose of analysis, etc.) in selecting an appropriate traffic simulation tool to use?	●		
Simulation Model Development				
9.1	Was the simulation work performed by in-house staff or by consultants?		●	
9.2	Was the full length (center lane-miles) of the study corridor modeled?	●	●	
9.3	Was a single network developed for the corridor or were sections modeled separately?	●		
9.4	Were there any improvement strategies that were NOT evaluated due to modeling difficulties?	●	●	
9.5	Did the project use a road network that was developed as part of another project?	●	●	
9.6	Were there road network elements that were not modeled?	●		
9.7	Were Application Programming Interfaces (APIs) or native scripting languages used to provide specific simulation functionalities?	●		
9.8	What functionalities were implemented using an API or native scripting language?	●		
9.9	Were the API or native scripting modules available prior to the start of the project?	●		
9.10	How often are APIs or native scripting languages used to expand simulation capabilities?	●		

Table 18 – Survey Questions (cont'd)

Question		T/M	PM	DM
9.11	How much time was dedicated to the simulation study?	●	●	
9.12	How do you rate the time spent collecting input data for the traffic simulation model?		●	
9.13	How do you rate the time spent coding the traffic simulation model (excluding calibration)?	●		
9.14	How do you rate the time spent calibrating the traffic simulation model?		●	
9.15	On a scale of 1 to 10, how important do you rate each of the following factors (specific model features, maturity of tool, purpose of analysis, etc.) in selecting an appropriate traffic simulation tool to use?		●	
Model Calibration				
10.1	Which element(s) do you normally consider when calibrating traffic simulation models?	●		
10.2	Which reasons may have contributed to calibration difficulties? Check all that apply.	●		
10.3	How well did the final base-year model accurately reflect existing traffic conditions?	●		
10.4	What criteria were used to determine whether the model was satisfactorily calibrated?	●		
10.5	Were any calibration criteria NOT met when the model was deemed successfully calibrated?	●		
10.6	How do you rate the time spent calibrating the traffic simulation model? (*same as 9.14*)	●		
10.7	Was there enough time allocated to developing an accurate simulation model?	●		
10.8	Were there enough resources available (personnel, budget) to develop an adequate model?	●		
Simulation Results				
11.1	How the number of run to execute was determined:	●		
11.2	What performance measures were outputted from the simulation model?	●		
11.3	What performance measures were computed through post-simulation data processing?	●		
11.4	Were there difficulties encountered during the scenario assessment process?	●		
11.5	Did the scenario results make sense?	●		
11.6	Did the Project Manager have a good understanding of what the simulation model could do?	●		
11.7	Were the expectations from the Project Manager realistic?	●		
Model Review				
12.1	How would you rate the quality of the simulation model that was developed (1 to 10 scale)?		●	●
12.2	Was there sufficient in-house expertise to review technical products from the traffic simulation?		●	●
12.3	Was outside consulting help sought for reviewing the simulation models?		●	
12.4	How much time (hours) was spent reviewing the simulation model?		●	●
12.5	To your knowledge were there critical modeling/calibration issues that could not be resolved?		●	
12.6	What were the modeling/calibration issues that could not be resolved?		●	
Use of Simulation Results				
13.1	What was the main outcome of the simulation evaluation?		●	●
13.2	How influential were the simulation results in decision-making activities?		●	●
13.3	What specific decisions were made based on the simulation results?		●	●
13.4	How important/helpful was the capability to graphically view simulation results?		●	●
13.5	How important/helpful was the capability to present animated simulation results?		●	●
13.6	Were there critical issues with the simulation model that affected the quality of the evaluations?			●
13.7	Did the simulation modeling meet initial expectations and accurately fulfill its role?		●	●
13.8	Could the same results have been obtained using deterministic (e.g., Highway Capacity Manual) or other analysis tools?		●	●
13.9	Were difficulties encountered because this was a first attempt at using traffic simulation?		●	●
13.10	Do you feel better results could have been obtained with additional training?		●	●
13.11	Has the simulation model been used for other projects?		●	●
Closing Comments				
14.1	Name of additional person who may be contacted for the survey?	●	●	●
14.2	Any comments/suggestions/questions regarding the survey?	●	●	●

4.4. SURVEY RESPONSES

Table 19 indicates how many individuals responded to the survey based on their role and corporate affiliation. Overall, 35 individuals provided responses. 21 worked for Caltrans, 3 for metropolitan planning organizations within California, and 11 for private consulting firms. Only one out-of-state consultant responded to the survey. The total number of responses within each category sums up to 39 since some individuals reported having a dual role, such as modeler/project manager or project manager/decision-maker.

33 of the 35 individuals who responded to the survey reported on experiences directly pertaining to the development of CSMP models. While most survey respondents provided answers pertaining to a specific project as instructed, others only provided answers reflecting their general experience. Table 20 lists the modeling efforts that are explicitly identified as a source of answers. These projects cover 15 of the 31 simulation-based CSMP operational evaluations listed in Table 2 in Section 2.4. Table 21 lists on the other hand the few non-CSMP modeling efforts that are covered in the survey.

Table 19 – Respondent Statistics

Project Role	Organization			Total Responses
	Caltrans	MPO	Consultants	
Decision-Makers	4	1	1	6
Project Managers	11	1	5	17
Technician/Modelers	9	2	6	16
Individual Respondents	21	3	11	35

Table 20 – CSMP Corridors Covered in Survey

Region	Corridor
District 4	• I-80 West (Paramics) • I-580 (Paramics) • US-101 San Mateo (FREQ 12)
District 5	• US-101 Santa Barbara (TransModeler)
District 7	• I-5 Los Angeles (VISSIM) • I-405 (Paramics) • US-101 Ventura (TransModeler)
District 8	• I-10 (VISSIM) • SR-91 Riverside (VISSIM)
District 10	• I-5/I-205 San Joaquin (CORSIM)
District 11	• I-5 North Coast (TransModeler) • I-805 San Diego (TransModeler)
District 12	• I-5 Orange County (Paramics) • I-405/SR-22/I-605 Orange County (Paramics) • SR-57 (Paramics)

Table 21 – Non-CSMP Corridors Covered in Survey

Non-CSMP Modeling Efforts
• I-5 freeway (4 mile section), Portland, Oregon • Various corridors and networks in Florida (Paramics/CORSIM)

4.5. SURVEY FINDINGS

This section presents a summary of the key statistics and findings that were extracted from the responses provided. Findings are summarized along the following categories:

- Agency general experience with traffic simulation;
- Simulation models used in surveyed projects;
- Respondent simulation experience;
- Scope of projects evaluated;
- Purpose of utilization of simulation models;
- Data collection;
- Model development;
- Model calibration;
- Model review;
- Use of simulation results; and
- Value of simulation effort.

4.5.1. AGENCY GENERAL EXPERIENCE WITH TRAFFIC SIMULATION

53% of public agency respondents and 85% of private consulting respondents indicated that their agency or firm regularly uses simulation. However, as shown in Figure 12, staff from public agencies among respondents rarely conducts simulations themselves. The predominant practice is to rely on a combination of in-house and external expertise. For the consulting side, while it was expected that a signification portion of modeling would be done in-house since they are typically contracted for this purpose, 4 out of 13 individuals (31%) indicated relying partly or wholly on other consultants.

Figure 13 and Figure 14 further compiles the travel demand and traffic simulation models reportedly being used by the agencies and consulting firms associated with the survey respondents. Among the responding agencies, the most commonly used traffic simulators are Paramics, VISSIM, TransModeler, CORSIM, Synchro/SimTraffic and FREQ 12. Model utilization by private consulting firms further appears to mirror the models being used by public transportation agencies.

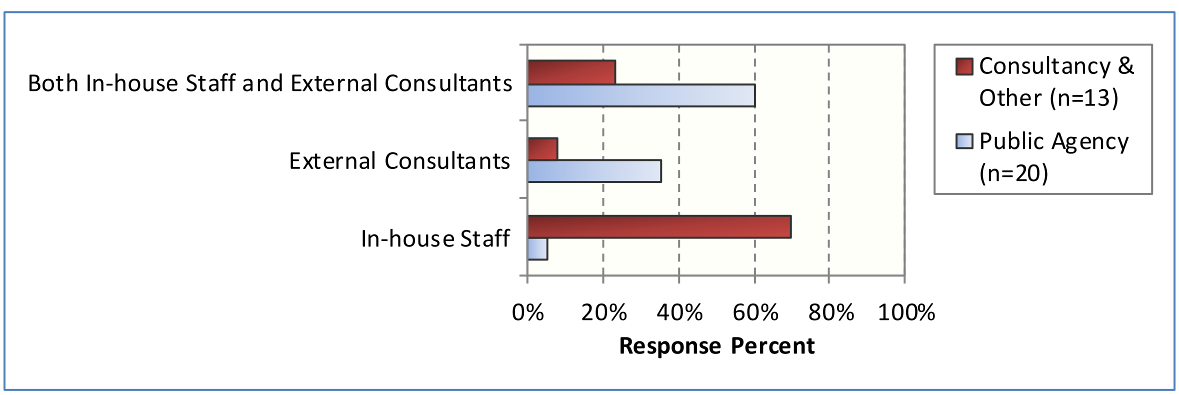


Figure 12 – Survey Results: In-House vs. External Modeling

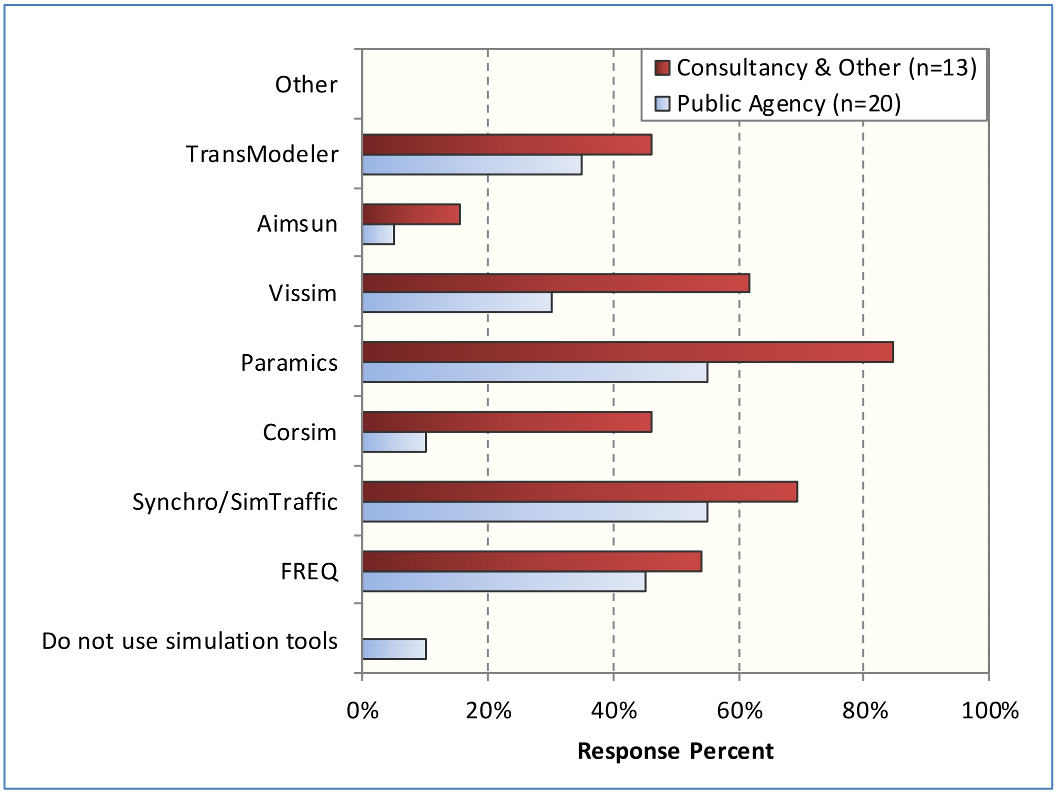


Figure 13 – Survey Results: Traffic Simulation Models Used by Public Agencies and Consulting Firms

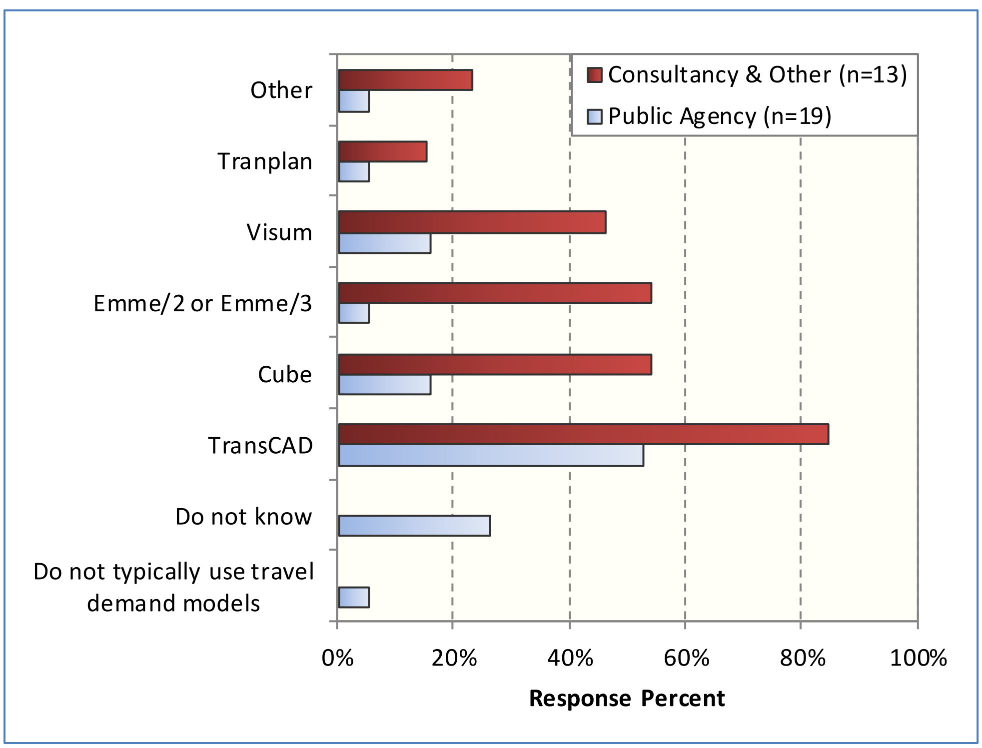


Figure 14 – Survey Results: Travel Demand Models Used by Public Agencies and Consulting Firms

4.5.2. SIMULATION MODELS USED

Figure 15 compiles the simulation models that were reportedly used to evaluate corridors operations in recent projects. Modeling efforts that relied on a combination of models are reflected in the response counts shown in the figure. As can be observed, Paramics and VISSIM were the dominant modeling tools. The distribution of models shown in Figure 15 differs somewhat from the general distribution of models being used by public agencies and private consulting firms reported in Figure 13 due to the continuously evolving capabilities of simulation tools. For instance, while many respondents have indicated that their agency or consulting firm had used FREQ 12 or CORSIM in the past, such models are nowadays much less frequently used due to the recent growth in popularity of microscopic models such as Paramics and VISSIM.

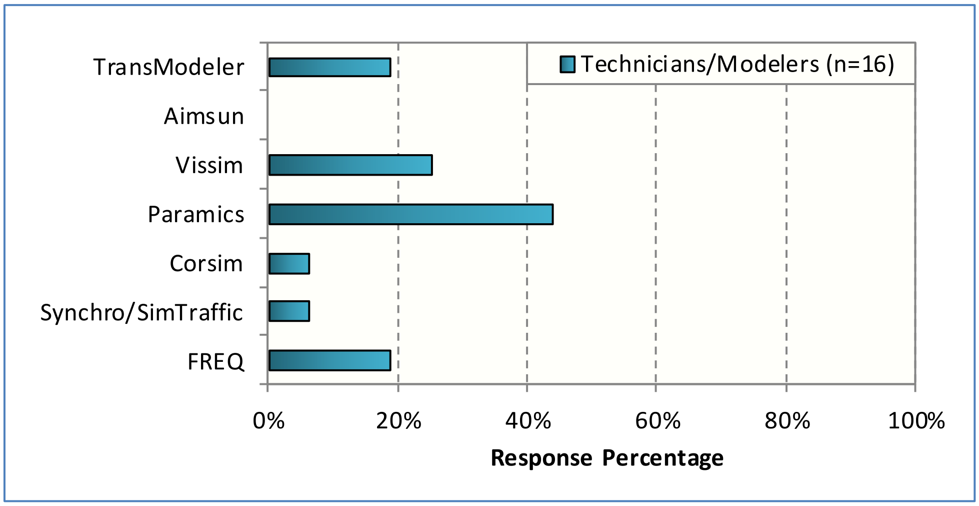


Figure 15 – Survey Results: Simulation Models Used in Surveyed Projects

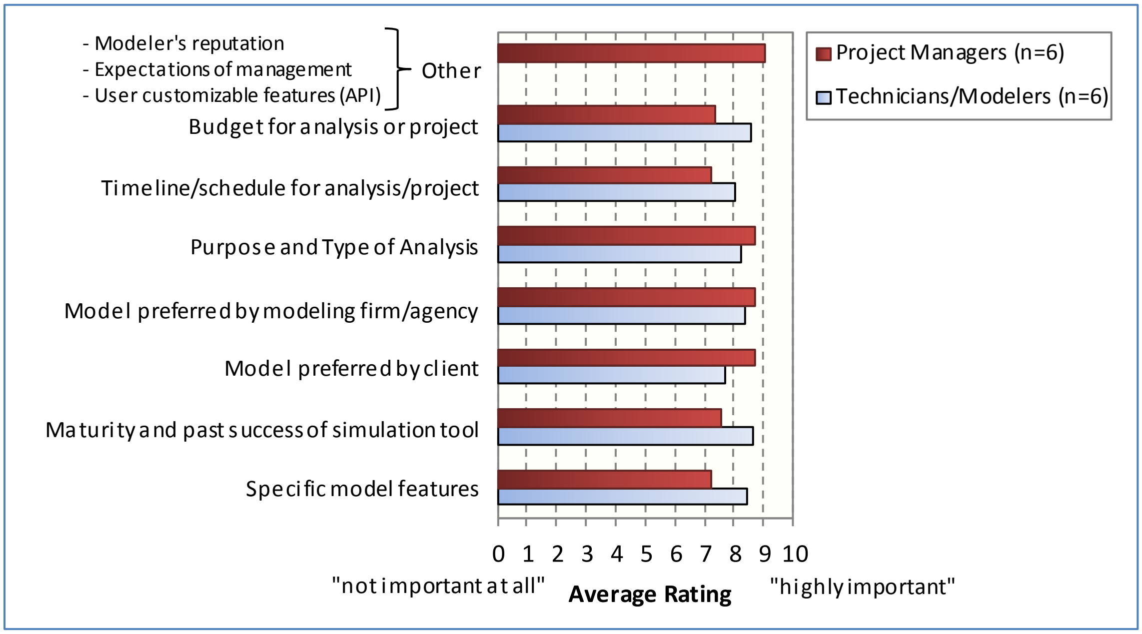


Figure 16 – Survey Results: Importance of Factors Used for Selecting a Simulation Model

Figure 16 further compiles the importance assigned by survey participants to various factors when deciding which simulation model to utilize for a particular project. Specific reasons cited include:

- Familiarity and level of proficiency of agency staff with the software;
- Demonstrated successful utilization of the model, particularly within the same region;
- Capabilities for modeling specific types of improvement projects;
- Time and budge available for data collection and model development;
- Simulation execution speed (particularly for projects involving FREQ 12);
- Ability to provide performance measures of interest to project stakeholders;
- Ability to import data from regional travel demand model; and
- Ability to re-use modeling from a previous project.

4.5.3. INDIVIDUAL SIMULATION EXPERIENCE/KNOWLEDGE

Figure 17 summarizes reported individual experiences with traffic simulation models. While most respondents have reviewed the results of simulations conducted by someone else (90% of respondents), far less experience was indicated with coding networks and running simulation models (55% of respondents in both cases). 24% of respondents considered themselves as beginners, 27% as having intermediate skill levels, 24% as experienced, and 21% as expert modelers. Reflecting the tendency for public agencies to rely on external consultants for simulation work, reported average levels of experience are noticeably higher for employees of private consulting firms than public agency staff.

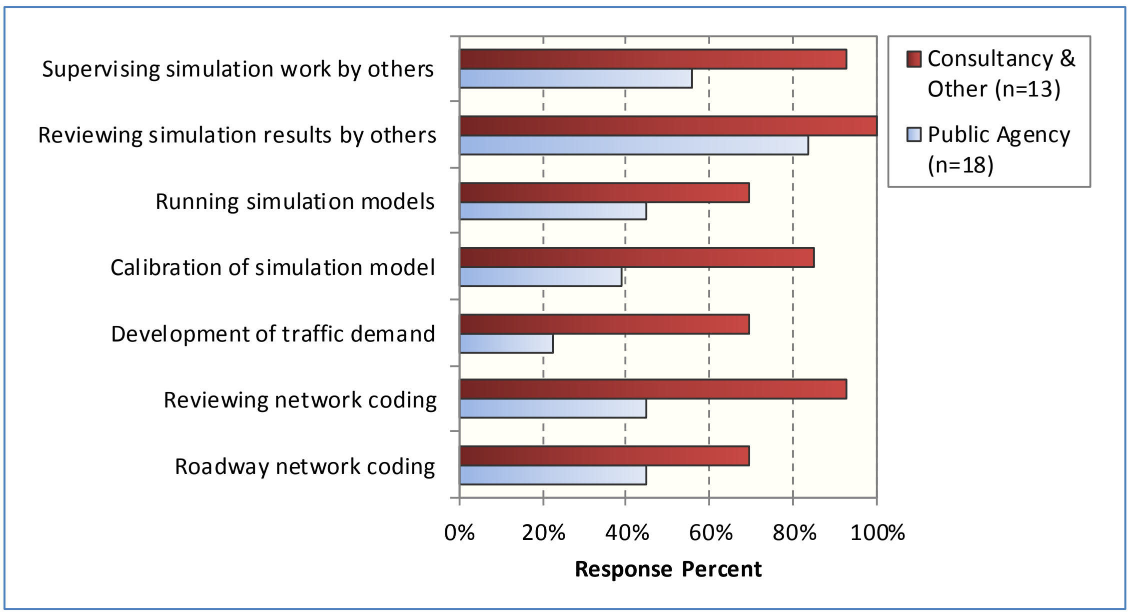


Figure 17 – Survey Results: Experience Using Traffic Simulation Models

4.5.4. SCOPE OF PROJECTS EVALUATED

Individual respondents were instructed to provide answers for specific projects. The following elements present a general characterization of the various projects used as reference for the survey responses:

- **Duration of simulation study** – Information provided for simulation modeling efforts lasting between 1 to 4 years, with an average duration of 21 months.

- **Length of modeled corridor** – Simulation models covering between 4 and 50 mi of freeway, with an average modeling length of 30 mi (3 corridors covering less than 20 mi, 8 corridors covering 20-29 mi, 9 corridors covering 30-39 mi, and 6 corridors covering 40 mi or more).
- **Number of interchanges** – Simulation models covering up to and 49 interchanges, with a majority of models covering between 20 and 36 interchanges.
- **Area covered by simulation model** – Modeling area ranging between 10 and 1000 square miles, with an average reported coverage area of 100 square miles.
- **Number of traffic O-D zones** – 20 to 300 zones.
- **Traffic congestion level** – Modeling efforts typically covering road networks high traffic demand, ranging from networks that have not yet developed significant congestion to networks operating in oversatured conditions.

7 out of 26 respondents (27%) indicated that the full length of the network or corridor that was to be modeled was eventually not coded. In most cases, budget and time issues were cited as prime issues for not doing so. Calibration difficulties with long corridors were also mentioned.

69% of respondents from consulting firms and 40% of respondents from public agencies further indicated that they involved in the modeling of corridors or road networks with over-saturated traffic conditions. The remaining respondents indicated having worked on the modeling of networks with moderately high traffic demand or traffic conditions approaching congestion. Very few respondents provided evaluations pertaining to the modeling of networks with traffic demands significantly below roadway capacity.

Simulation models were frequently used to evaluate operational conditions that can present significant simulation challenges. While traffic simulation models are generally designed to handle congestion, simulating such conditions often bring forward the modeling limitations of each simulation tools, particularly with respect to their underlying driver or flow behavioral models. Many of these limitations are simply a reflection of the complex nature of driver behavior, and particularly of the fact that drivers often display different behavior in congested rather than free-flow traffic conditions.

4.5.5. PURPOSE OF SIMULATION MODEL UTILIZATION

Figure 18 presents the types of projects that have been evaluated using simulation. Most respondents indicated having used simulation to evaluate capital improvement projects and operational improvement strategies. Simulation has also been used to help evaluate transportation policies and design operational or control strategies. A more detailed breakdown of improvement projects considered is provided in Figure 19 and summarized below[1]:

- Nearly all respondents indicated having used simulation to evaluate capacity improvement projects, typically the addition of freeway lanes (81% of respondents) or auxiliary lanes (93%). Truck-climbing lanes were evaluated in only 22% of the surveyed projects.
- The most widely evaluated traffic operational strategies are the addition of HOV lanes (89% of respondents) and addition or improvements of ramp meters (93% of respondents).

[1] Note that 8 of the 35 survey respondents did not indicate evaluation of any strategy; their responses were not counted towards the percentages calculated of Section 4.5.5.

- Evaluation of enhanced traffic management incidents evaluated in about half the projects between reported on.
- Evaluation of travel demand management strategies was not widespread, likely due to the inability of most traffic simulation models to model time-demand shifts.
- Transit-related improvements were evaluated in some projects. This included transit signal priority, changes in transit service frequency, and larger transit park-and-ride facilities.
- While many traffic simulation models have recently added the ability to simulate pedestrians and/or cyclists, very few projects evaluated upgrades to pedestrian and bicycle facilities. This is likely due to the relatively recent introduction of these features.

A significant number of respondents reported being unable to evaluate specific improvement strategies due to modeling difficulties. Some projects abandoned efforts to model HOT lanes and advanced ramp metering systems due to the inability of the simulation model to replicate adequately the desired systems. Other respondents indicated an inability to readily model transit-related improvements and consider improvement projects involving parallel arterials. Many of these limitations can be attributed to the relative novelty of the strategies considered, which resulted in few models offering desired built-in capabilities. It is therefore possible that future versions of the simulation models may facilitate the modeling of such systems.

Figure 20 further compiles how simulation results were considered to evaluate transportation projects. Simulation results were most frequently used to help evaluate the effectiveness of individual operational strategies or most effective strategies within a group, help produce cost/benefit ratios, and help prioritize improvements. Some respondents also reported using simulation to help justify previously approved projects or to produce data supporting financial requests for specific projects incorporated into simulation models.

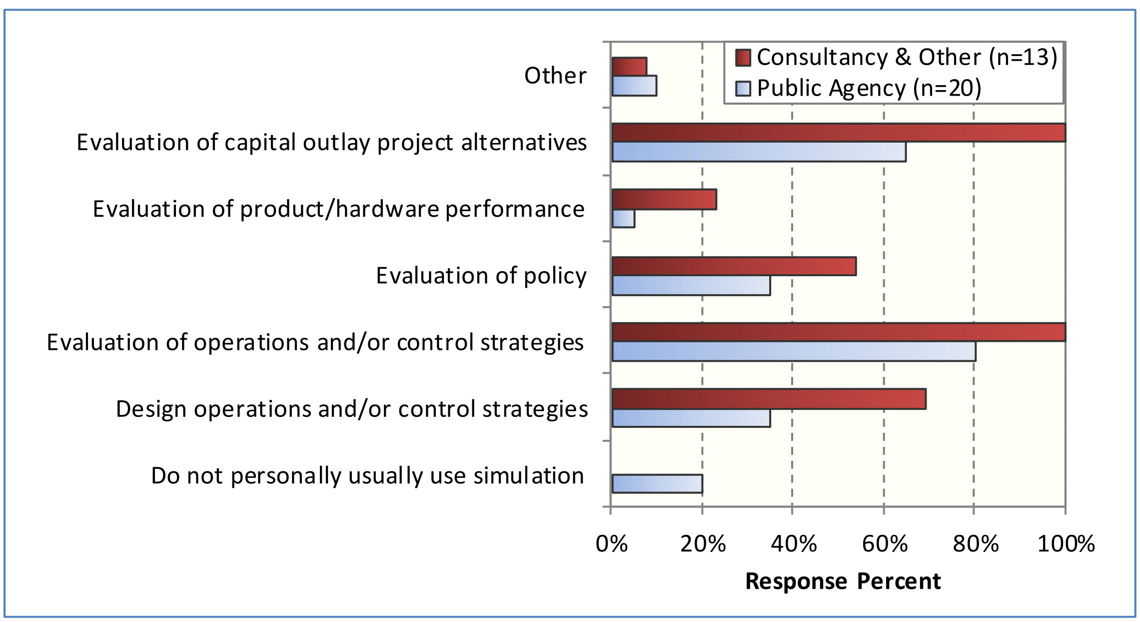


Figure 18 – Survey Results: Types of Projects Evaluated

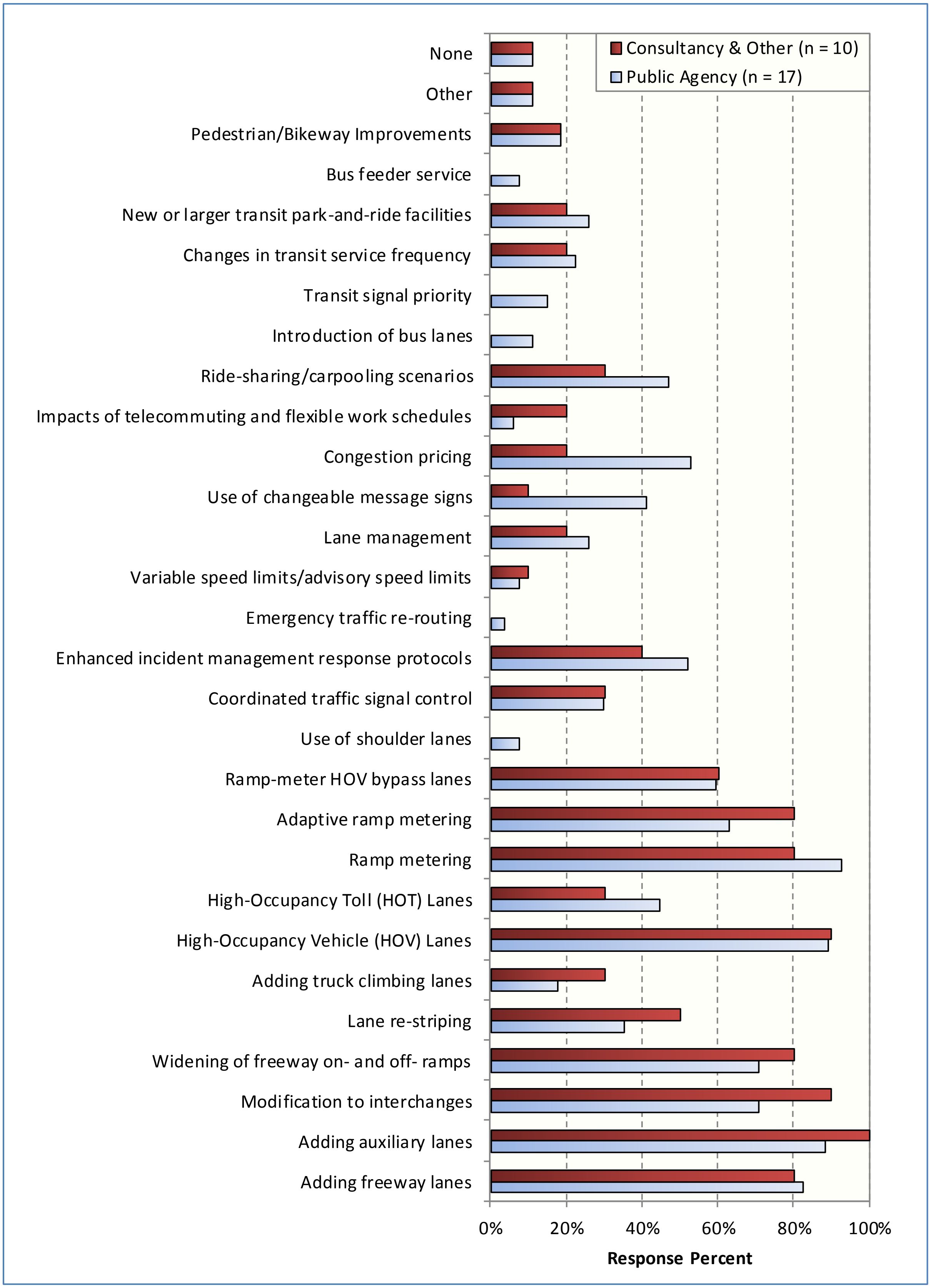


Figure 19 – Survey Results: Improvement Projects Considered

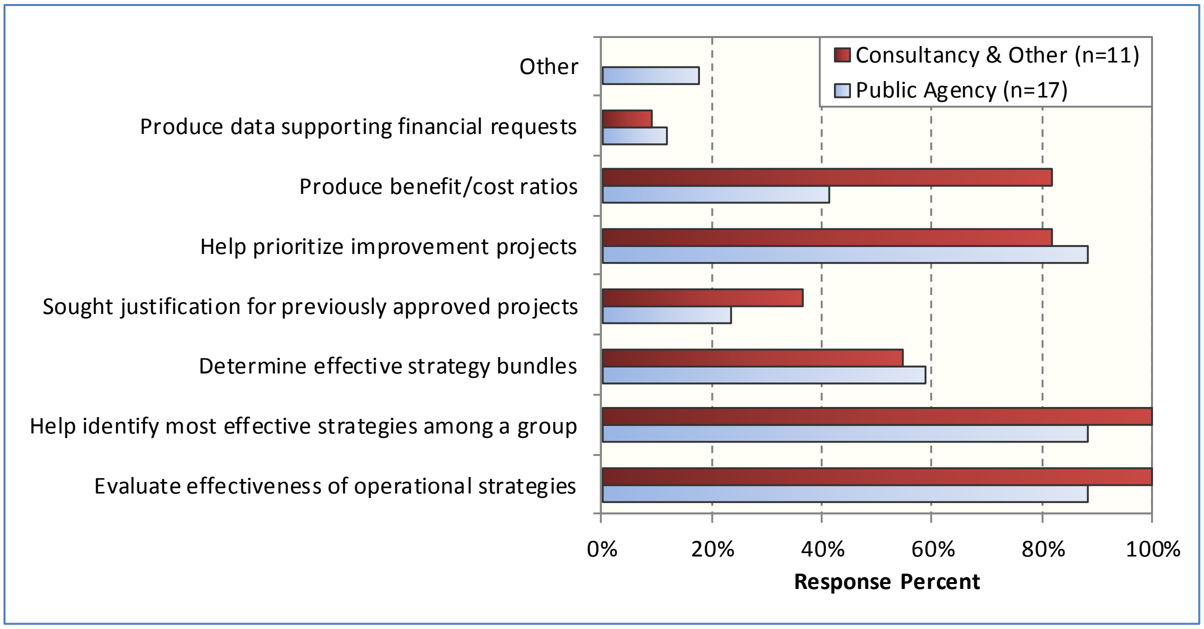


Figure 20 – Survey Results: Purpose of Utilization of Traffic Simulation Models

4.5.6. DATA COLLECTION

Not surprisingly, survey respondents indicated that the majority of data collection efforts relied on data provided by PeMS stations, volume counts and traffic counts. Regional travel demand models were also frequently cited as the primary source of information for the modeling of traffic demand. A large majority of respondents further indicated that regional transportation agencies were generally supportive of the modeling effort. There are mentions of local agencies providing travel demand data, allowing the use of an existing simulation model that had been developed through a previous project, providing modeling expertise, providing help reviewing the developed models and, in some cases, even providing some financial support. Only one respondent indicated obtaining no support from the regional transportation agency.

Only 12 respondents provided information about the percentage of time and funds spent collecting data. With respect to time, individual respondents indicated that data collection consumed between 5 and 33% of the total project duration, with an average of 17%. With respect to budget, data collection consumed between 0% and 33% of the total budget, with an average of 15%. For each project, the stated percentage of funds dedicated to data collection generally matched the proportion of time associated with the activity. However, since no information has been provided on whether the time or cost figures include activities that have carried out to process and analyze the collected data, it is unclear whether each of the reported statistics strictly covers data collection activities or also includes some post-collection activities.

12 out of 15 respondents further indicated that data collection was done either entirely by a hired consultant or by a combination of in-house staff and hired consultant. In this case, both public transportation agencies and consulting firms appear to have equally relied on external consultants specializing in data collection. These statistics are in accordance with an early survey described in Sbayti & Roden (2010), in which 68% of survey respondents indicated reliance on external contractors for data preparation and conversion.

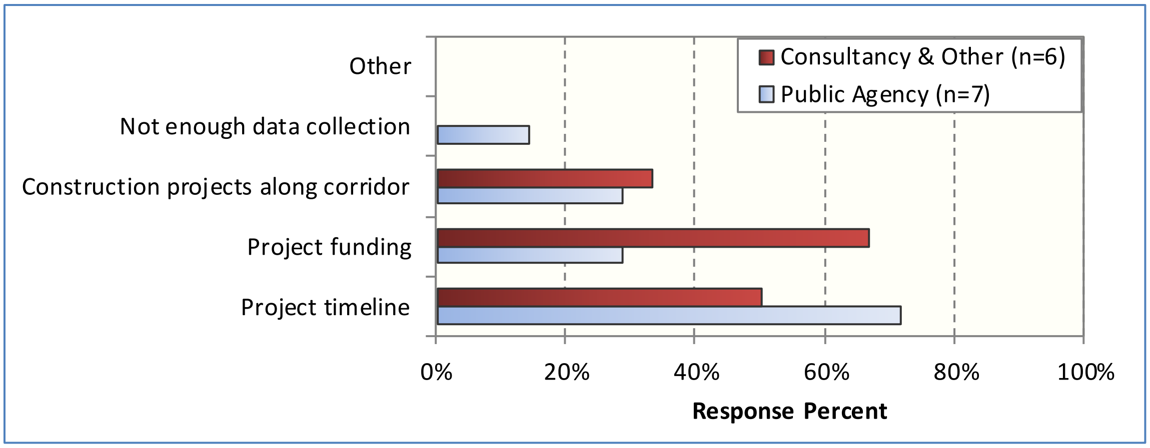


Figure 21 – Survey Results: Factors Affecting Data Collection

Figure 21 presents the factors that were stated to have affected data collection. Not surprisingly, the two main factors are time and budget. Construction activity is mentioned as an influential element by two respondents, while one respondent indicated that the consultant hired to develop the simulation model did not spend enough time or resources collecting data. In addition to the above factors, many respondents further indicated problems with the collected data, such as:

- Contradictions between data from various sources or a single source (15 respondents);
- Unrealistic data values (7 respondents); and
- PeMS stations provided a high proportion of imputed data (5 respondents).

4.5.7. MODEL DEVELOPMENT

As shown in Figure 22, 9 out of 12 public agency respondents (75%) indicated that the development of the traffic simulation model development was contracted out. 3 out of 6 respondents from private consulting firms (50%) further indicated that either part or the entire simulation model used in the evaluation project came from a previous modeling effort.

On the use of Application Programming Interfaces (APIs), 12 of 19 respondents indicated that APIs were used to provide additional modeling capabilities not initially offered with the simulation tool. Figure 23 summarizes the functionalities that were typically added. Most of the improvements sought to implement specific ramp metering control programs and replicate the operation of loop detection systems. Some improvements were also made to enhance driver behavior. About two thirds of the respondent indicated using APIs either frequently or for every project. However, these APIs are not always developed as part of a modeling project, as 50% of the respondents indicated using APIs that had already been available at the beginning of a modeling project.

Respondents indicated that a one- to two-year commitment was typically required to complete a simulation study, with the time spent developing a model highly dependent on the manpower committed to the task. When asked to rate the acceptability of this effort, 17 individuals out of 24 (71%) indicated that the modeling effort was either not time consuming at all or acceptable despite the required time. On the other end, 7 respondents (29%) judged the effort very time consuming. As can be observed from the data in Figure 24, consultants generally appear to have been less critical of the time requirements than public agency staff, likely due to the fact that they were more frequently responsible for the model development.

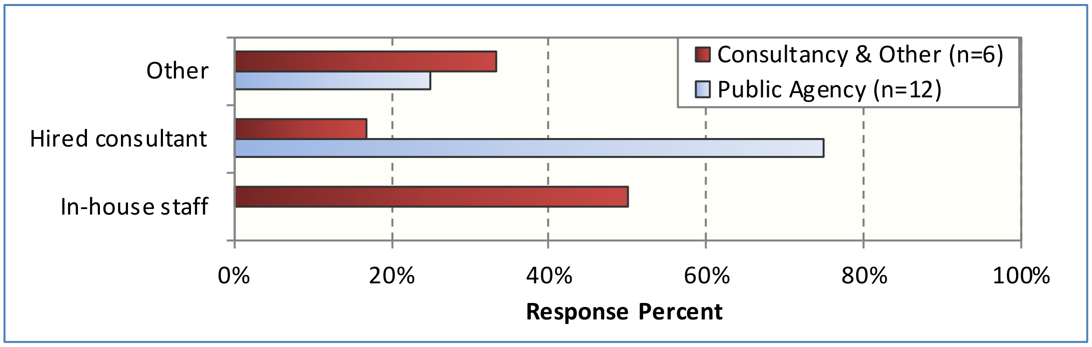


Figure 22 – Survey Results: Responsibility for Model Development

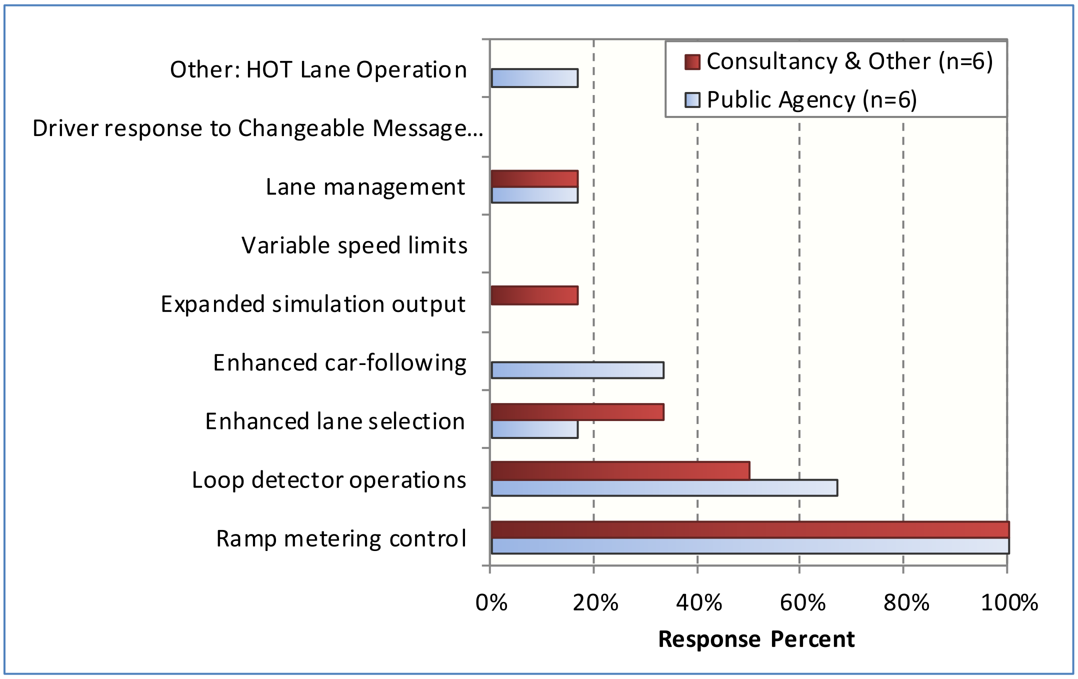


Figure 23 – Survey Results: Functionalities Modeled Through APIs

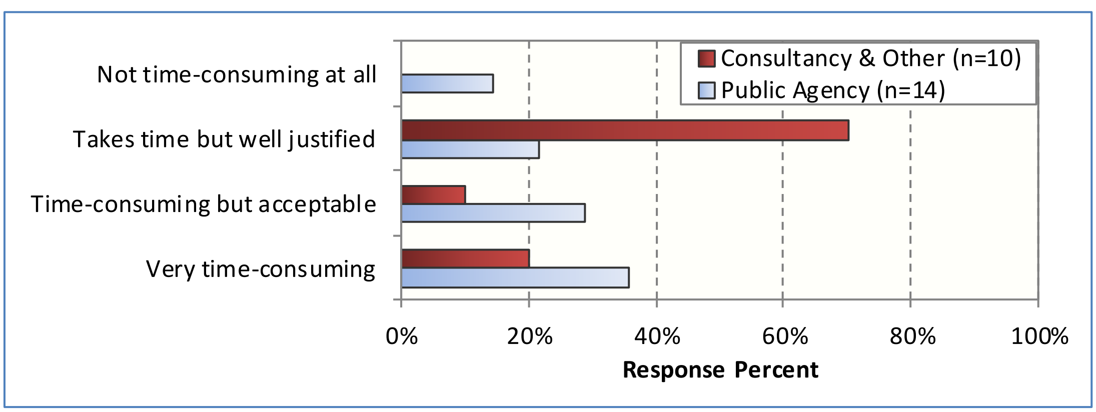


Figure 24 – Survey Results: Value of Modeling Effort

4.5.8. MODEL CALIBRATION

Figure 25 indicates that 15 out of 16 survey respondents (94%) reported using the guidelines recommended by the FHWA or Caltrans for the calibration of simulation models. This is not surprising given that the use of these guidelines is often imposed within modeling contracts. The only individual who reported not using the FHWA/Caltrans guidelines was referencing a FREQ modeling effort for which the primary calibration criteria were adequately replicating the location, start time and end time of bottlenecks, as well as travel times along the corridor within each 1-hour interval. While the FHWA/Caltrans guidelines have not been formally applied, the selected calibration criteria can be viewed as a partial application of the guidelines.

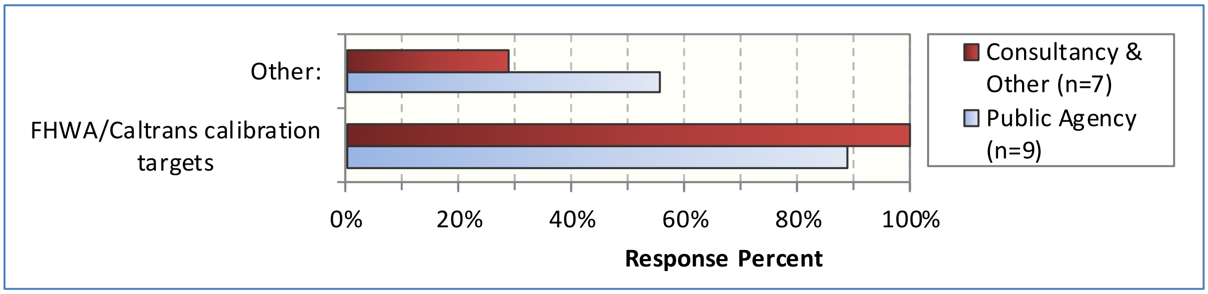


Figure 25 – Survey Results: Calibration Targets

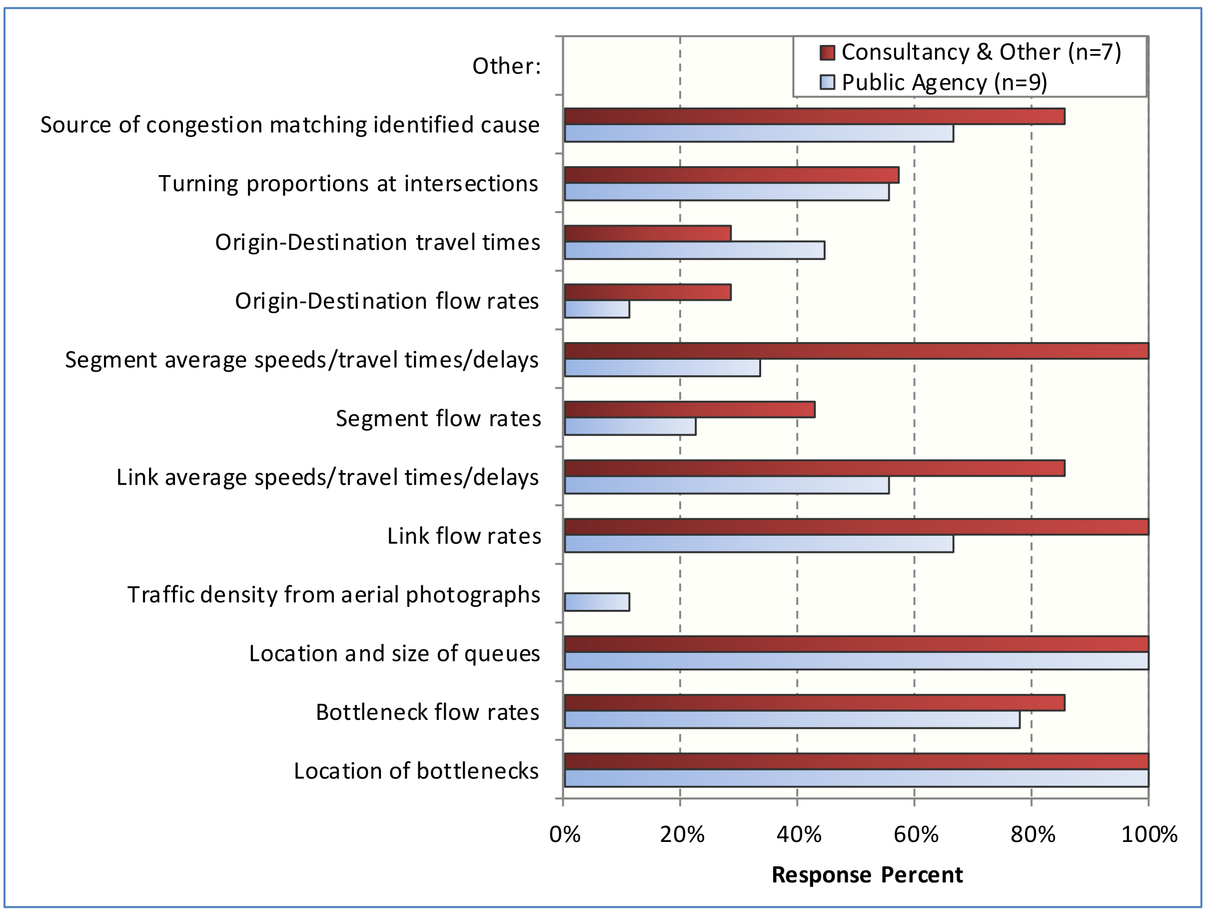


Figure 26 – Survey Results: Calibration Items

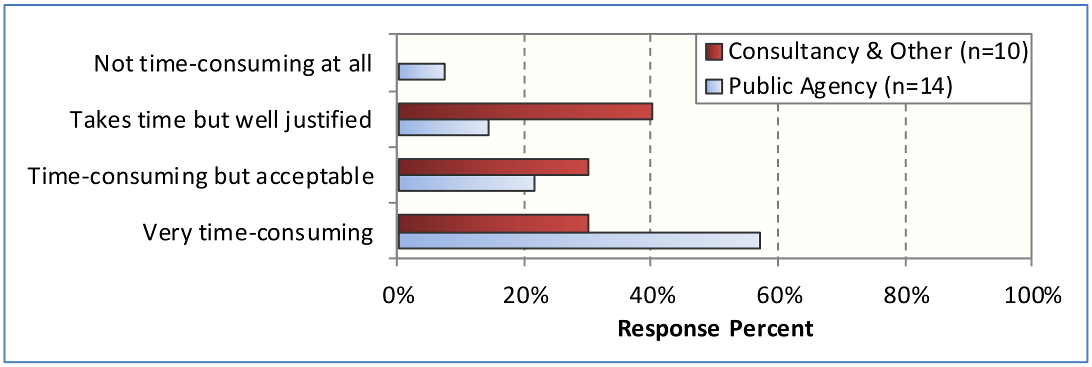


Figure 27 – Survey Results: Value of Calibration Effort

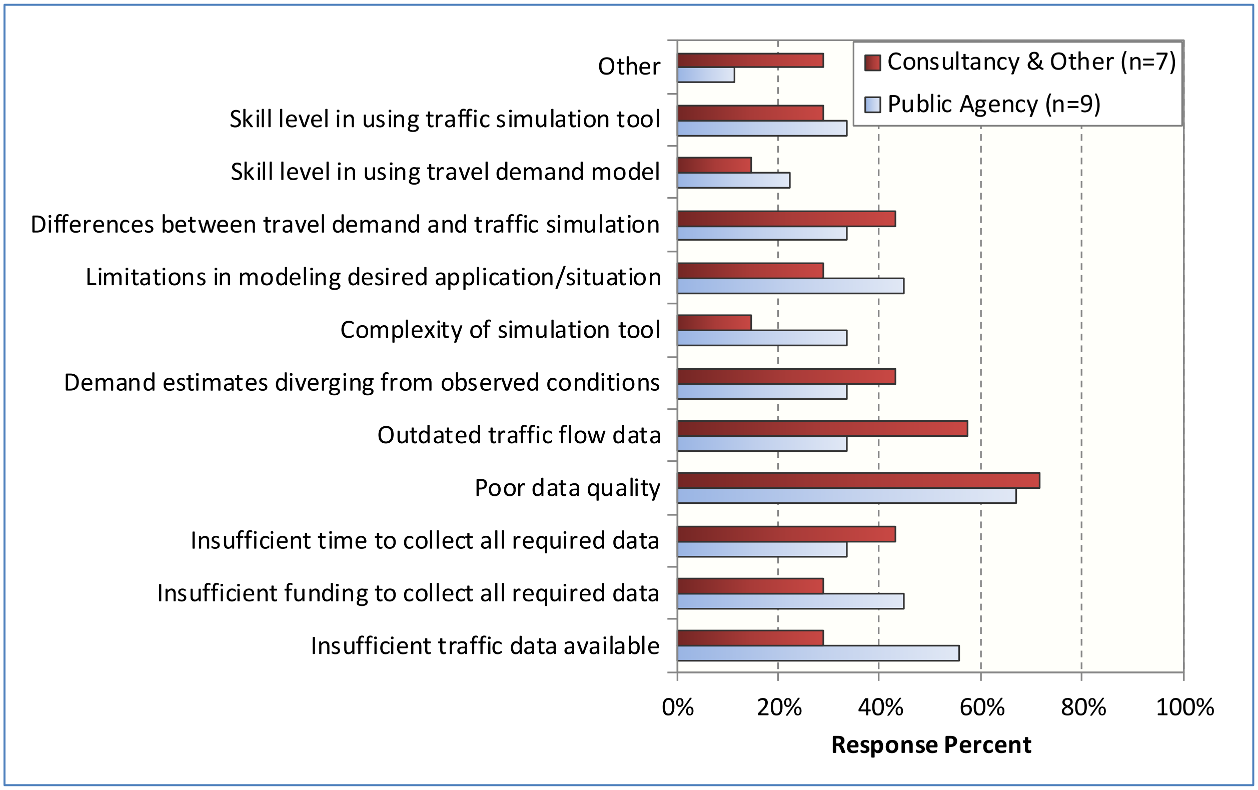


Figure 28 – Survey Results: Sources of Calibration Difficulties

A notable observation from the data in Figure 25 is that 7 of the 16 respondents (44%) also indicated using additional calibration guidelines to supplement the FHWA/Caltrans guidelines. Some of the reported additional guidelines include:

- Use of a lower GEH value for calibrating flows at bottlenecks;
- Speed matching targets for bottlenecks;
- Engineering judgment; and
- Awareness of traffic conditions within the modeled network.

Figure 26 further presents the parameters typically considered when calibrating simulation models. While many of the considered elements reflect the FHWA/Caltrans guidelines, a notable observation is the importance on calibrating the location, cause and operation of bottlenecks. It can also be observed that O-D travel time times and flow rates were considered as calibration elements in a fair number of projects.

Calibration is often cited in practice as a time-demanding activity. The survey mirrors this assessment. As shown in Figure 27, 11 out of 24 respondents (46%) indicated that calibration was either time consuming or very time consuming. This includes 8 persons from public agencies (57% of answers within group) and 3 persons from consulting firms (30% of answers within group). According to the data in Figure 28, the two most frequently cited factor increasing the time required for calibration are poor and outdated data. These identified factors further highlight the need for quality data in any modeling project. Other reasons include modeling limitations, lack of calibration experience, and insufficient time and/or funding. Similar attitudes towards calibration were found in the survey conducted by Sbayti & Roden (2010), where 65% of respondents reported that model calibration was a major difficulty in the development of simulation models.

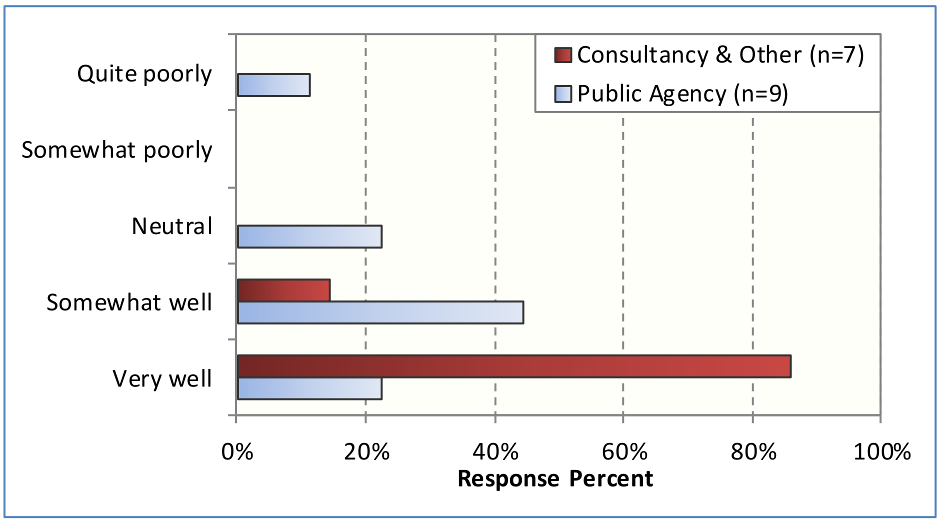


Figure 29 – Survey Results: Assessed Quality of Final Model

When asked how well the calibrated base-year model replicated existing traffic conditions, responses drastically differed between individuals from public agencies and consulting firms. As shown in Figure 29, 6 out of 7 respondents (86%) from consulting firms found the existing traffic conditions to be replicated very well, while only 2 out of 9 individuals (22%) of public agencies had a similar assessment. A similar difference in opinion is obtained in the perception of how well the project's calibration criteria (FHWA or others) were met. While 86% of respondents from consulting firms indicated that all calibration criteria were satisfied, only about 44% of public agency respondents through so. Only one individual stated that a model poorly replicated observed conditions.

On a separate question, 13 out of 16 modelers (81%) indicated believing that the results produced by the calibrated model made sense. However, one individual with a contrary opinion indicated that the results occasionally made sense and occasionally not, but did not provide further explanation. A possibility is that questionable data may have been used in the modeling. Other reported problems included simulations producing high flow rates during an incident than without it, difficulties in adequately modeling merging behavior, and the egress and ingress points of HOV lanes, and scenarios producing unexpectedly low travel times or delays.

Finally, 5 respondents out of 16 (31%) indicated that in their opinion insufficient time had been allocated to developing an accurate model. 6 of 15 respondents (40%) further indicated not enough funding or personnel had been available for the intended scope of the project.

4.5.9. MODEL REVIEW

Figure 30 indicates that survey respondents are generally satisfied with the developed simulation model. Satisfaction is noticeably higher for respondents from consulting firms, likely due to the fact that these include a much higher proportion of model developers, who tend to have a higher esteem for their work than project managers or decision-makers.

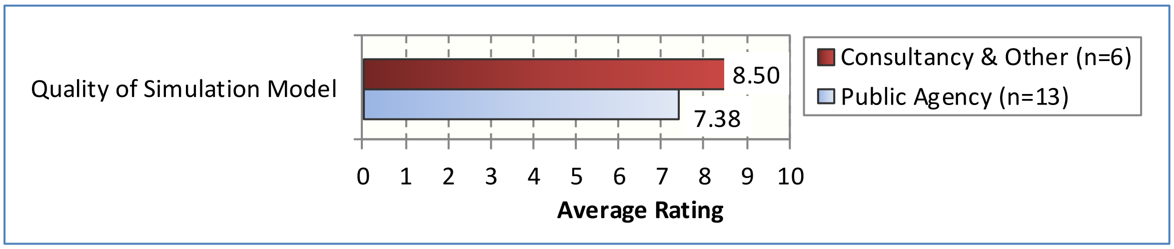


Figure 30 – Survey Results: Satisfaction with Final Simulation Model

16 respondents out of 20 (80%) thought there was sufficient in-house expertise to review the developed models. Contrary opinions primarily commented on a lack of time or personnel to dedicate to the review. 65% of the respondents further indicated that outside help was sought for the review.

A few respondents specified the amount of time dedicated to model review. Answers provided ranged from about 40 hours to several hundreds of hours. This range likely reflects the varying complexities of corridors models, as well as varying amounts of problems that may have been encountered.

6 respondents out of 16 (38%) finally indicated that some calibration issues that were left unresolved in the models that were eventually approved. These issues included:

- Removal of excessive amount of vehicles due to blockage;
- Inadequate replication of traffic merging at HOV ingress and egress points; and
- Scenarios producing lower than expected delays.

4.5.10. USE OF SIMULATION RESULTS

Respondents generally indicated extracting a variety of information from simulation outputs. Key performance measures include link flow rates, link flow density, link/segment travel times, bottleneck locations, queue lengths, VMT, and VHD. While many simulation models now offer the ability to estimate vehicle fuel consumption and air pollutant emissions (often through optional modules), very few respondents indicating using traffic simulation model to directly obtain such measures.

While simulation models can report various link-based and network-based statistics, a certain amount of post-simulation data processing is generally expected to develop specific performance measures of interest to project stakeholders. Performance measures that survey respondents indicated obtaining through post-simulation processing fuel consumption and vehicle emission estimates (typically by feeding traffic simulation data into other models), compilations of statistics for groups of links forming segments of interest, and speed contour maps.

As shown in Figure 31, survey respondents further had varying assessments on the importance of the ability offered by microscopic and mesoscopic simulation models to present animations to an audience. Out of 18 project managers and decision-makers, 9 individuals (48%) indicated that the ability to obtain animations was either important or crucial. At the other end, 4 individuals (21%) also indicated that developing tables from simulation output data was sufficient.

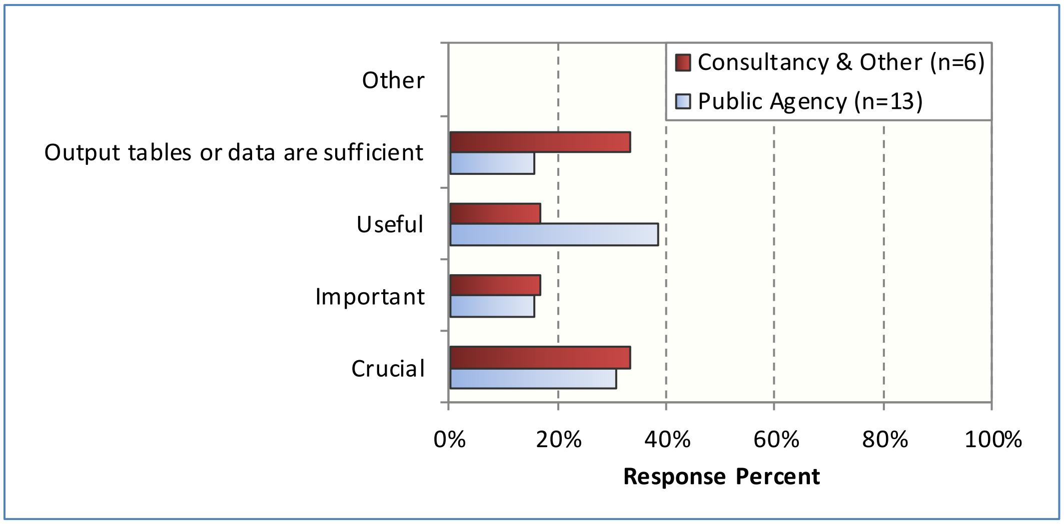


Figure 31 – Survey Results: Importance of Animations

4.5.11. VALUE OF MODELING EFFORT

Figure 32 indicates that 15 of the 19 project managers and decision-makers who responded to the survey generally perceived that the simulation modeling met their initial expectations and accurately fulfilled its role. A number of these individuals indicated that the modeling effort met initial expectations for time and expenses, and that simulation results were helpful in identifying projects to pursue. The four negative opinions were all from individuals from public agencies. Negative comments expressed by these individuals include difficulties in simulation model calibration, model specific traffic management strategies (advanced ramp metering), and high time and budgetary requirements.

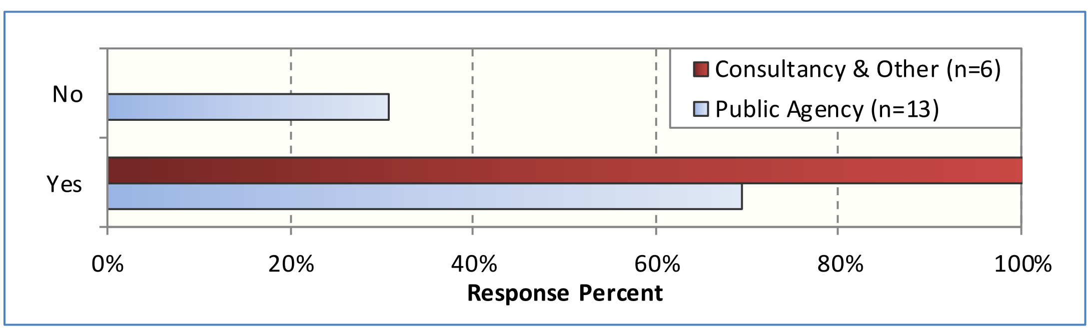


Figure 32 – Survey Results: Value of Simulation Study

As further indicated in Figure 33, 18 out of 20 project managers and decision-makers further thought that the simulation results had some influence on decision-making activities. Only two individuals, both associated with Caltrans indicated that the simulations were not influential at all. When asked whether similar project evaluations could have been done using deterministic analysis tools, such as the Highway

Capacity Software (HCS), 14 out of 17 individuals (82%) indicated that they did not believe it was possible, thus highlighting the importance of using of microscopic or mesoscopic models for corridor evaluations. In the survey conducted by Sbayti & Roden (2010), similar attitudes towards simulation were found, as most (70%) respondents "believed that the simulation tools highlighted inadequacies in traditional modeling" (e.g., the ability to model queues, bottlenecks, etc.).

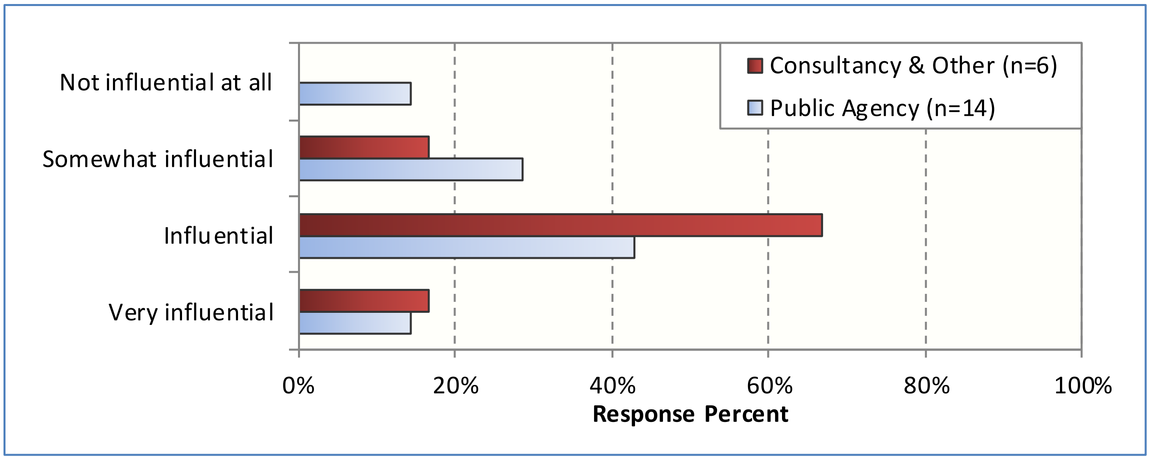


Figure 33 – Survey Results: Influence of Simulations on Decision-Making

While the overall assessment is positive, the range of answers highlights the varying nature of modeling projects conducted. While some projects can be modeled with relative ease, projects seeking to address innovative control strategies for which existing simulation models offer no built-in capabilities, to model highly congested networks, or to model networks for which only few reliable information are available, are bound to encounter more difficulties. 7 out of 19 project managers and decision-makers indicated that they thought that difficulties were encountered specifically because the modeling effort was a first attempt at using traffic simulation to evaluate corridor improvements. This suggests that fewer problems could be expected in a second evaluation phase, particularly if already developed models are re-used.

About half the project managers and decision-makers from public agencies indicated that they felt that better results could have been obtained with additional training. This may be a reflection of a lack of adequate knowledge with traffic simulation modeling capabilities at public agencies. Within the pool of respondents from private consulting firms, only two respondents out of 6 (33%) indicated that additional training could have improved results.

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5. CSMP CASE STUDIES

To better understand how traffic simulation has supported the development of CSMPs, a detailed review of modeling and simulation activities associated with six CSMP corridors was conducted. The reviewed corridors are listed in Table 22 and illustrated in Figure 34. These corridors were chosen based on their utilization of a variety of simulation tools, their complexity, and need to address fairly high congestion levels.

For each corridor, the review covered the following elements:

2. Final CSMP report;
3. Comprehensive performance assessment report;
4. Initial task orders from Caltrans for simulation modeling;
5. Simulation modeling and calibration reports;
6. Technical memos; and
7. Interviews with modelers, project managers and decision-makers.

Table 22 – List of CSMP Studies Reviewed

Corridor	Caltrans District	Location	Primary Simulator	Corridor Characteristics	CSMP Lead	Model Developer
I-80 West	4	Alameda County	Paramics	20-mile corridor extending from the end of the San Francisco Bay Bridge in the south to the Carquinez Bridge in the north.	Consultant A	Consultant A
US-101	4	San Mateo County	FREQ 12	58-mile corridor extending from the Candlestick Park interchange in the north to the SR-85 interchange in the south.	Caltrans District 4	Consultant B
I-5 North and I-5 South	7	Los Angeles County	VISSIM	Corridor covering a 14-mile section extending from the Orange County boundary in the south to the I-710 interchange in the north, and a 27-mile section extending from the I-10 interchange in the south to the I-210 interchange in the north.	Consultant C	CH2MHill
I-205 / I-5	10	San Joaquin County	CORSIM	40-mile corridor combining a 13-mile section of I-205 and 27-mile section of I-5 between the boundary with Alameda County and city of Lodi.	Consultant A	Consultant A
I-805	11	San Diego	TransModeler	29-mile corridor running between the I-5 interchange near San Ysidro to the south and I-5 interchange near Sorrento Valley to the north.	Consultant C	Consultant D
I-405/ SR-22/ I-605	12	Orange County	Paramics	Corridor covering a 25-mile section of I-405 and 16-mile section SR-22 running from the Los Angeles County boundary to the I-405/I-5 interchange.	Consultant C	Consultant E

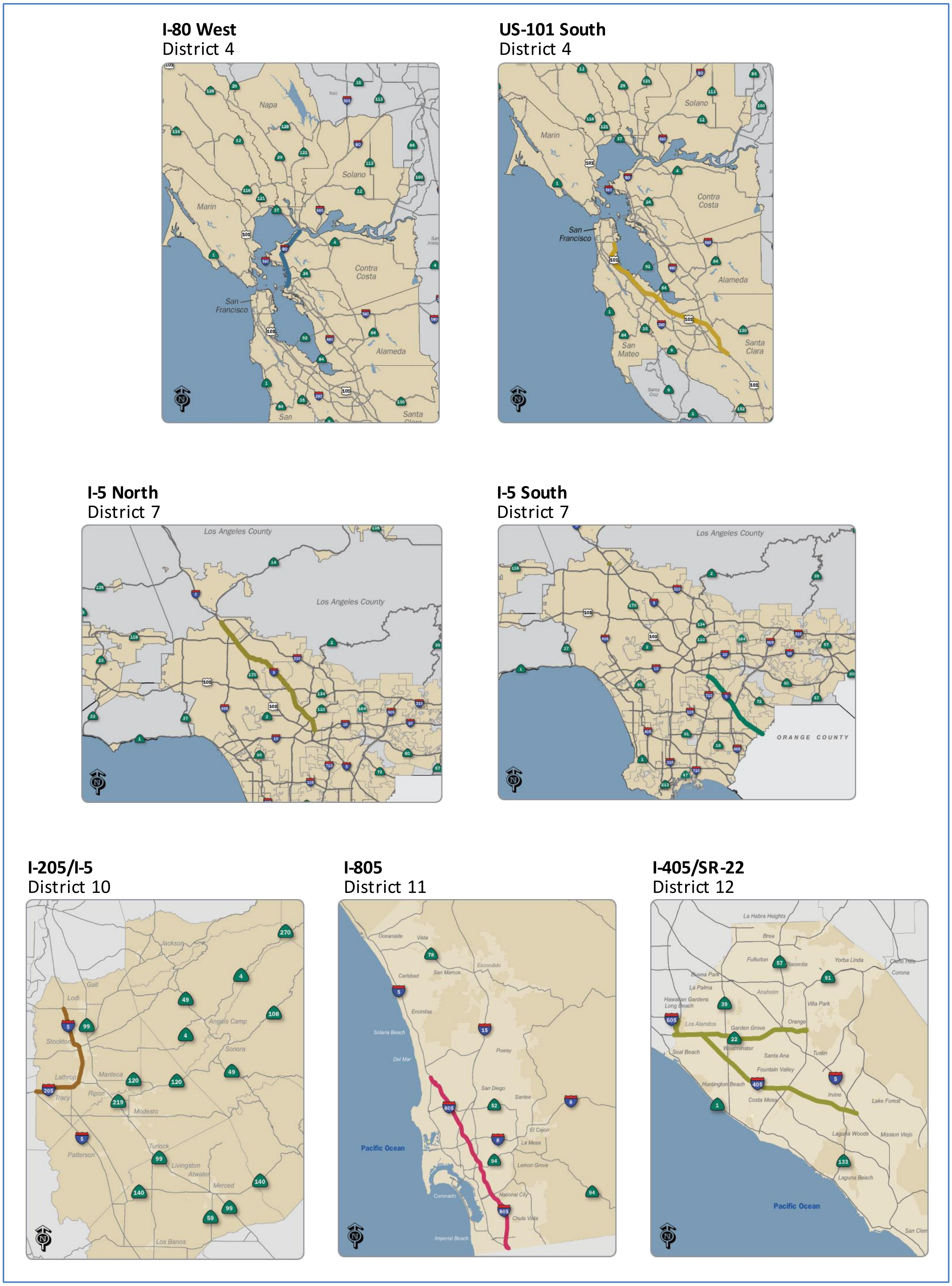


Figure 34 – CSMP Corridors Included in Detailed Review

All the simulation models that were developed using Paramics, VISSIM, CORSIM and FREQ 12 were reviewed by the project team. Models developed using TransModeler were not reviewed due to the unavailability of a software license at the University of California. This review was not a formal model audit by only a general model assessment. Each review included an examination of the parameters used to calibrate the underlying driver behavior models, sample model runs to assess its general operations, and an examination of the simulation outputs.

The main findings of the review are presented in the following subsections. Elements discussed include:

1. Model development process;
2. Selection of modeling software;
3. Geographical scope of modeling;
4. Input data collection;
5. Data validation;
6. Demand modeling;
7. Error checking;
8. Model calibration;
9. Peer review and model approval process;
10. Improvement projects considered;
11. Development of scenarios;
12. Model plug-in requirements;
13. Model application;
14. Evaluation of scenarios;
15. Prioritization of improvements;
16. Presentation of evaluation results;
17. Impacts of modeling efforts on corridor recommendations; and
18. Perceived cost-effectiveness of simulation effort.

5.1. MODEL DEVELOPMENT AND UTILIZATION PROCESSES

Figure 35 illustrates the general process that appears to have been followed for the development and utilization of simulation models. While some small variations were observed across projects, the processes generally followed the guidelines outlined in the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (Dowling, Skabardonis and Alexiadis, 2004). Typical model development and utilization steps included:

1. **Identification of project scope** – Identification of the project's purpose, spatial extent, appropriate model, level of expertise, and staff time.
2. **Selection of modeling approach and simulation model** – Identification of the type of simulation (microscopic/mesoscopic/macroscopic/hybrid) and specific simulation software to be used.
3. **Data collection and preparation** – Collection of data required for the development of the simulation model. This step includes collecting data from traffic monitoring systems, conducting field data collection, reviewing base maps, retrieving information from data warehouses, or requesting data from specific agencies. It also includes checking data validity, processing and reducing data to extract specific information, and formatting data for their use in simulation models.

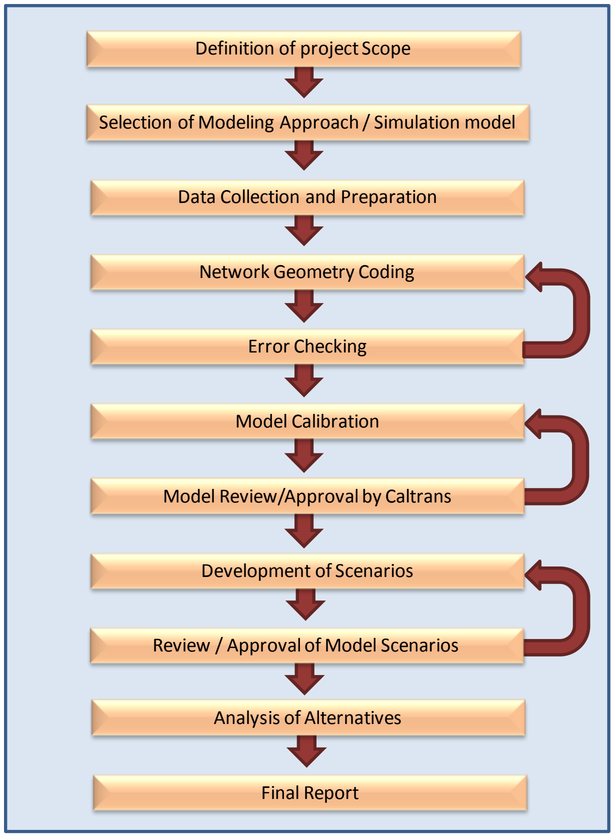


Figure 35 – Simulation Study Process

4. **Base model development** – Creation of links and nodes representing the road network, definition of the geometric characteristics of each link and node, insertion of traffic control elements, specification of travel demand matrices, and setting of simulation parameters.
5. **Error checking** – Checks for coding errors that can affect the execution of simulations.
6. **Model calibration** – Adjustment of model parameters to reproduce traveler behavior and traffic performance. This involves the establishment of calibration targets, selection of appropriate calibration parameters to reproduce observed roadway capacities and route choice patterns, and calibration of model parameters so that its performance matches field observations.
7. **Model approval by Caltrans** – Approval of developed model by Caltrans before it could be used to evaluate improvement strategies. In many cases, the approval process was done iteratively with the model calibration.
8. **Evaluation of alternative scenarios** – Application of the approved calibrated model to assess improvement strategies against a baseline scenario using agreed-upon performance measures.
9. **Development of final report** – Writing of final CSMP report outlining various findings.

5.2. SELECTION OF SIMULATION SOFTWARE

Various simulation models were used to evaluate the selected corridors. The microscopic Paramics, VISSIM, TransModeler and CORSIM models were used for five corridors, while one corridor relied on the macroscopic FREQ 12 model. The use of different simulation models was expected given that different consultants were contracted to perform the evaluations and that the CSMP operational evaluations were managed by different staff within each District.

Below is a description of the key factors that were considered when determining which simulation model to adopt for each the corridors:

- **I-80 West** – Two key criteria that were considered were 1) extensive use in the area covered by the corridor, in part to facilitate stakeholder acceptance with the selected model, and 2) the ability to develop realistic animations for public meetings. These criteria led to a discussion to utilize either Paramics or VISSIM. Eventually, Paramics was recommended based on its built-in incident modeling capabilities, its more efficient coding method, its organized data reporting, and its built-in handling of dynamic routing assignments. The fact that this model had also been used in other regional studies was also considered.
- **US-101 San Mateo** – The FREQ 12 macroscopic model was selected partly because staff from Caltrans District 4 and the Metropolitan Transportation Commission (MTC) had prior experience with it. Budget and scheduling constraints were also decision factors, as there were concerns that using a microsimulation model could lead to a complex and time-demanding endeavor.
- **I-5 North and I-5 South Los Angeles County** – VISSIM was selected based on the familiarity of Caltrans District 7 staff with the tool and the fact that it had been successfully used to conduct simulation studies within the region, notably along a section of I-5.
- **I-405/SR-22/I-605 Orange County** – Information from Caltrans suggests that Paramics was chosen because District 12 staff had prior experience with the software and good knowledge of its modeling capabilities. There is also indication that Paramics might have been selected to leverage prior modeling work using the software.
- **I-205/I-5 San Joaquin** – Modeling with CORSIM was requested by Caltrans District 10 to leverage the fact that the District already had a CORSIM license and staff trained to use the software. Furthermore, there was no individual within the District with adequate experience with more advanced microscopic simulation models when the CSMP operational evaluation was initiated. This created concerns that the District may not have the staff or budget available to learn how to use a new microscopic simulation model.
- **I-805 San Diego** – TransModeler was selected based on its compatibility with TransCAD, the software implementing SANDAG's travel demand model, as well as its ability to replicate the various traffic improvement strategies that were considered for the corridor, such as freeway ramp metering, traffic signal coordination, and managed lane operations.

A general observation is that five primary factors appear to have influenced the decisions regarding which simulation tool to adopt:

- Familiarity of agency or consulting staff with simulation model;
- Ability to evaluation specific corridor improvements;
- Ability to leverage prior work;
- Prior or current utilizations of the model in other regional projects;
- Compatibility with regional travel demand model; and
- Time and budget constraints.

It must be emphasized that not all factors have necessarily affected decisions equally on every corridor. While some factors were dominant, others may have been ignored.

5.3. GEOGRAPHICAL SCOPE

Table 23 presents a general summary of the roadway elements that were modeled within each corridor. To facilitate the discussion, illustrations of the simulation models that were developed as part of the CSMP operational evaluations are presented in Figure 36 to Figure 41. All corridors featured at a minimum a modeling of the freeway mainline and on/off ramps. This was expected given the focus on freeway operations. However, differences do exist in the extent to which freeway interchanges and the road network surrounding the freeway(s) at the center of each corridor were modeled. In some cases, differences are due to limitations associated with the selected simulation tool. However, time and budget constraints, as well as the availability of modeling data, are likely to have played a significant role in decisions shaping the extent of the road network to model.

Table 23 – Geographical Scope of Modeled Networks

	I-80	US-101	I-5	I-405 / SR-22	I-205 / I-5	I-805
Number of network models	**1**	**1**	**2**	**2**	**1***	**1**
Freeway mainlines	●	●	●	●	●	●
Freeway ramps	●	●	●	●	●	●
Full modeling of freeway interchanges	●		●	●	●	●
Modeling of intersecting arterials approaching the freeway mainline	●		●	●	●	●
Modeling of intersecting arterials up to at least one signalized or stop-controlled intersection	●		P_i	●	●	●
Modeling of alternate routes via parallel arterials	●			P_r	●	●

* - CORSIM uses separate internal models to simulate traffic behavior on freeways and arterials

P_i – Some intersections adjacent to interchanges were modeled, but only at a few locations

P_r – Partial modeling (Modeling of short alternate route near the I-405/SR-22/I-605 interchange only)

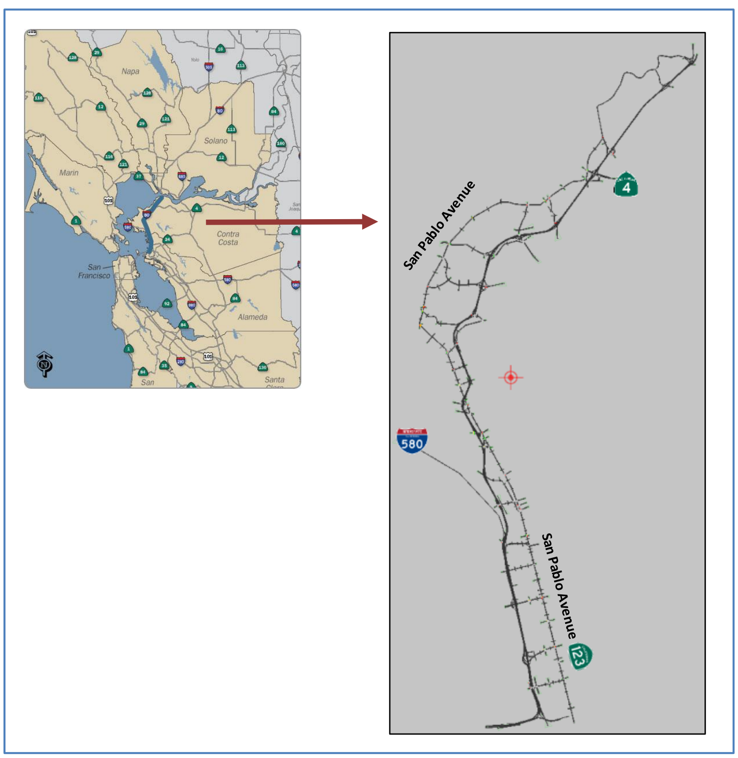


Figure 36 – I-80 West Paramics Modeling

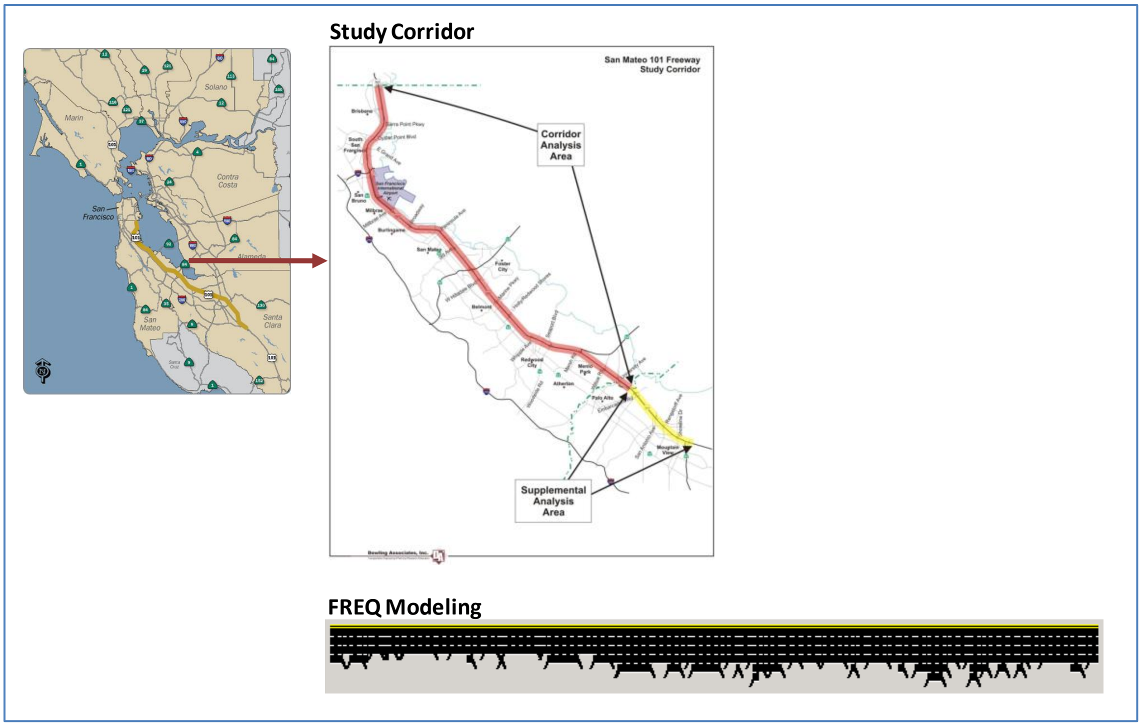


Figure 37 – US-101 FREQ Modeling

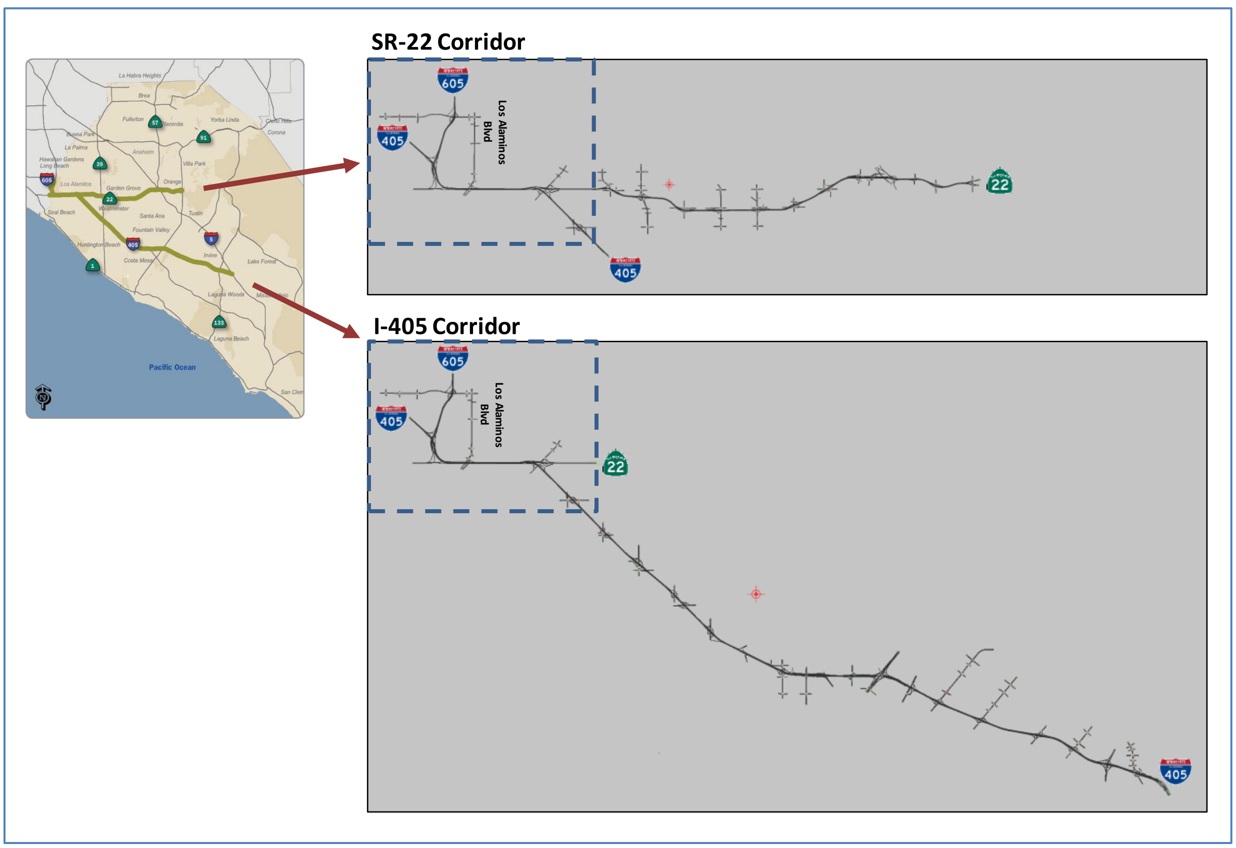


Figure 38 – I-405/SR-22 Paramics Modeling

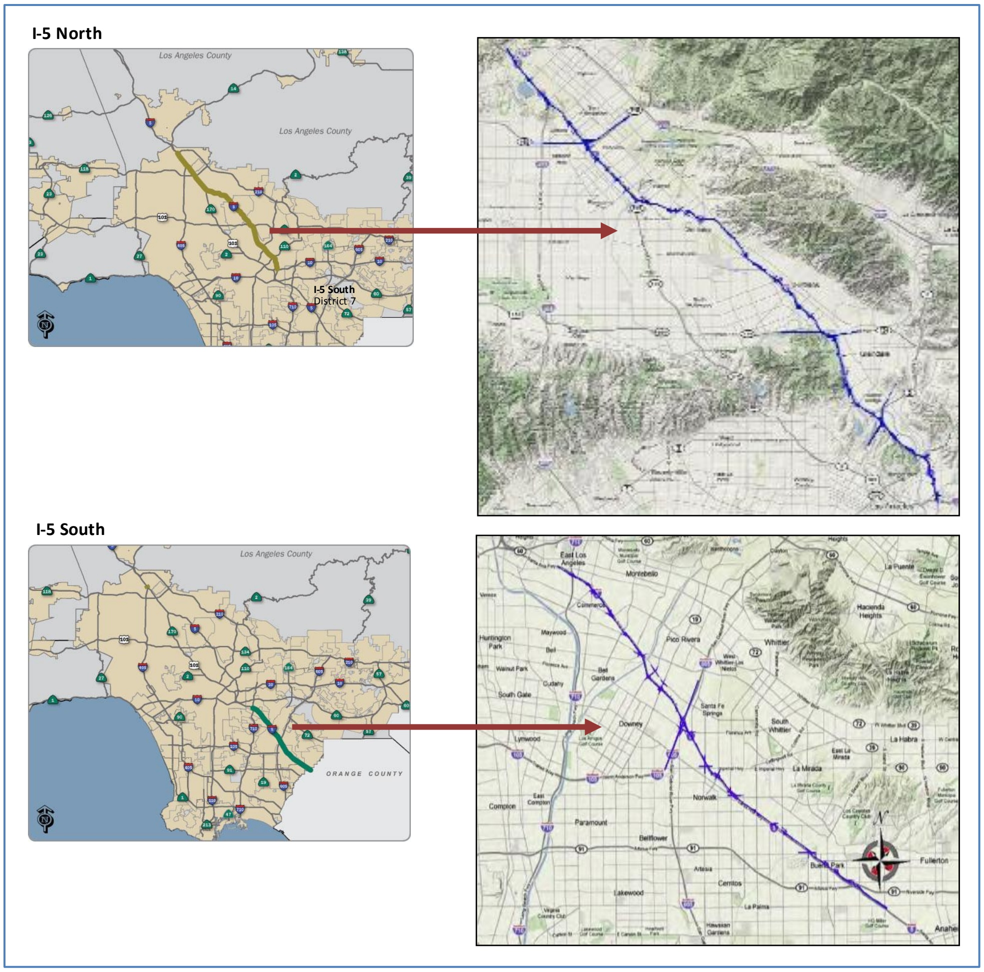


Figure 39 – I-5 North and I-5 South VISSIM Models

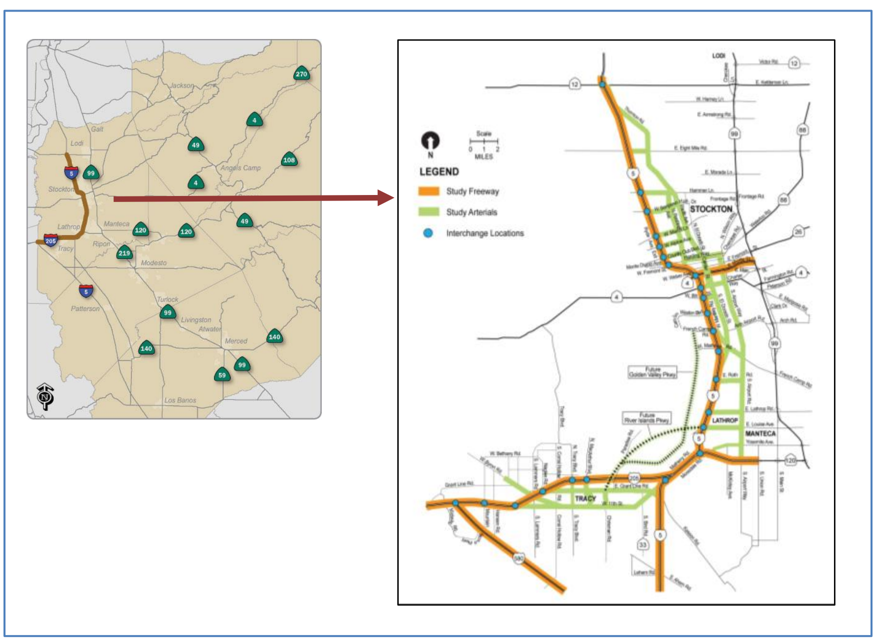


Figure 40 – Geographical Scope of I-205/I-5 CORSIM Modeling

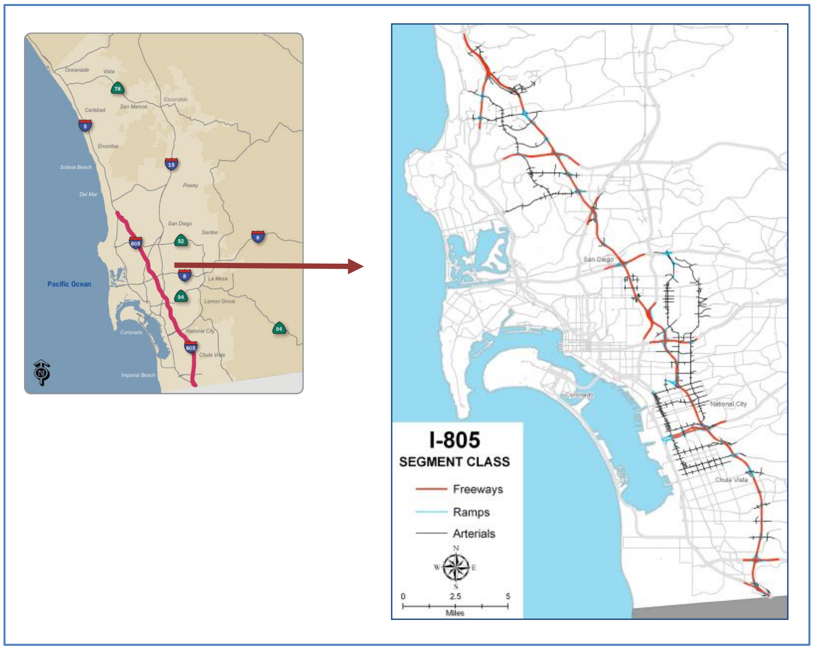


Figure 41 – Geographical Scope of I-805 TransModeler Modeling

Among the six reviewed corridors, the US-101 is the only one for which the modeling was strictly restricted to the freeway mainline and ramps. This was a project-based decision reflecting the fact that the CSMP operational evaluations primarily sought to evaluate potential improvements along the freeway mainline under the existing interchange and arterial configurations. There was little interest in evaluating interchange improvements since the county had recently completed or was already working on a series of improvements. It was further perceived that El Camino Real, the major arterial parallel to US-101, had already been optimized and did not warrant further improvements.

While it is typically desirable to develop a single simulation model for each corridor, this was not always possible. Separate models were developed for different sections of a corridor in two cases:

- For the I-5 corridor, separate models were developed for the sections extending north and south of downtown Los Angeles. This split was rationalized by the nature of the freeway system in downtown Los Angeles, which features many overlapping and crossing freeways. Modeling of a single freeway would have not been useful in this case.
- For the I-405/SR-22 corridor, separate models with a small overlapping portion were developed for the I-405 and SR-22 freeways. Two main considerations led to this approach. The first was a concern regarding the ability to cordon the regional travel demand model and develop logical O-D matrices based on the relative positioning of the two freeways. The second was uncertainty regarding the computer processing power required to evaluate future-year scenarios used a single model. Since microscopic simulation models typically run slower when simulating large numbers of vehicles, there were concerns that long run times could prevent the timely delivery of simulation results. Splitting the network in two not only allowed to reduce the number of vehicles being simulated in each model, and thus to shorten simulation times, but also to use different computers to evaluate each corridor.

Another common desire was to expand the modeling as far as possible on both sides of the modeled freeways. However, time and budget constraints, as well as the need for extensive data collection along surrounding arterials, effectively limited what could be modeled. For corridors considering only improvements along the freeway mainline or ramps, another argument was that the study area needed to extend past the ramp terminal intersections only where adjacent intersections in close proximity of the interchanges would affect the ramp flows.

Finally, only four corridors included a partial or complete modeling of arterials parallel to the main freeway. In most cases, these arterials were modeled with the intent to evaluate route diversion effects at key network locations resulting from freeway improvements. The most extensive modeling efforts were for the I-80, I-805 and I-205 corridors. The I-80 corridor includes a full modeling of San Pablo Avenue, an arterial running parallel to I-80 along the entire length of the modeled section. While the I-805 corridor also models several parallel arterials, the use of alternate routes is only possible along certain sections of the corridor. Due to time and budget constraints, the decision was made here to only model arterials commonly used as diversion routes when congestion becomes severe on I-805. Finally, while the I-205/I-5 corridor includes an extensive set of parallel arterials, it should be kept in mind that CORSIM simulates traffic on freeways and arterials using different simulators, and that arterial traffic is essentially routed by a game of chance at each intersection, not according to a pre-calculated path.

5.4. INPUT DATA COLLECTION

Table 24 compiles the data most commonly used to develop simulation models. The data is categorized using the same classification as the one presented in Section 3.4, with the exception of the addition of a category pertaining to scenario development:

- **Network geometry** – Data describing various geometric aspects of the study corridor, such as the location of intersections, road widths and curvatures, grades, the number of lanes on each segment, equipment used for monitoring traffic performance, etc.
- **Traffic control** – Data characterizing the operation of traffic signals and ramp meters, as well as any priority rules that may be used, such as priority schemes for transit vehicles at intersections.
- **Travel demand** – Data characterizing fleet composition, the distribution of flows between the various origin and destinations nodes, and how travelers to select a path within a network.
- **Network performance/calibration** - Data characterizing how traffic behaves along roadway elements, such as volumes, speeds, travel times, location of bottlenecks, etc.
- **Scenario development** – Data used to model the improvement projects that are to be evaluated and how various projects may be combined to develop specific evaluation scenarios.

The collected data are generally consistent with the requirements outlined in *Data Framework for Freeway Corridor Performance Evaluation* (Systems Metrics Group *et al.*, 2010). This consistency was expected since the data framework described in the document was developed by two consulting firms that actively participated in the CSMP modeling efforts. The framework is notably based on modeling experiences in the Sacramento, San Diego, Los Angeles, San Bernardino and Orange County areas. Experiences from an earlier demonstration project led by the California Center for Innovative Transportation along the I-880 corridor in Oakland were also considered (West. 2010).

Table 24 – Data Collected for CSMP Simulation Modeling Efforts

Category	Sub-Category	Data Item
Network geometry	Freeway geometric elements	• Number of lanes • Purpose of lane (general traffic, HOV vehicles, managed lane, etc.) • Location of on/off freeway ramps • Location of lane additions, lane drops, auxiliary lanes • Link length • Link curvature • Placement of traffic signs along roadway links
	Arterial geometric elements	• Number of lanes • Lane utilization (through lane, left-turn lane, etc.
	Traffic Monitoring	• Location and type of traffic sensors
Traffic control	Intersection control:	• Type of intersection control (stop sign, yield sign, traffic signals) • Type of traffic signal control (fixed time, actuated, traffic responsive) • Signal timing plan • Arterial signal coordination plan
	Ramp metering:	• Type of ramp meter • Metering plan • Location of traffic sensors
Demand Modeling	Fleet characteristics	• Vehicle mix • Truck percentages and/or volumes • Vehicle occupancy
	Traffic zones	• Zone boundaries
	Travel patterns	• O-D flow matrices • Network entry flows, if O-D matrices are not used • Mode shares (*only if for models including transit or non-vehicle modes*)
	Freeway traffic patterns	• Freeway mainline counts • Freeway ramp volumes
	Arterial traffic patterns	• Link counts along major arterial segments • Intersection turning counts
	Transit operations	• Transit routes • Service headways/schedules
Network performance	Freeway traffic behavior	• Volume, speed and occupancy data from mainline detector stations • Freeway ramp volumes (on-ramps, off-ramps) • Travel times along freeway segments
	Arterial traffic behavior	• Volume and speed data along arterials and at intersections from manual or tube counts • Travel times along arterial segments
	Bottlenecks	• Time bottleneck stations • Location and extent • Cause of bottleneck
Scenario Development	Improvement projects	• List of planned and programmed projects • Project concepts • Expected delivery date • Cost of project • Design Plans

Major sources of data for the reviewed CSMP modeling efforts include the following:

- **Caltrans Performance Measurement System (PeMS)** – PeMS was the primary source of data for all corridors. This system collects and stores loop detector data from over 25,000 individual traffic detectors located along major freeways across California. The system currently has over 10 years of data and offers various built-in capabilities for historical data analysis. Data from various local agencies are also integrated into the system, allowing analysts to access information on incidents, lane closures, toll tags, census traffic counts, vehicle classification, weigh-in-motion stations, and roadway inventories.
- **Field traffic counts** – Field traffic counts were conducted to obtain data from where PeMS data were not available. Manual counts or automated tube counts were conducted to collect volume data on freeway ramps and along arterials, as well as turning counts at major intersections. Some counts were also conducted to obtain vehicle classification data or assess vehicle occupancy. Depending on the corridor, the collected data covered either solely the AM and PM peak periods or an entire 24-hour period. However, due to time and budget constraints, field data collection efforts were typically restricted to cover only one, two or three weekdays.
- **Probe vehicle and floating car runs** – Tachometric runs were conducted for all corridors to collect travel time data where this information could not be obtained from PeMS or other sources. Data collections were typically structured to collect travel time samples from both the AM and PM peak periods over two or three weekdays. Across the various corridors, the total number of travel time runs conducted varied somewhat significantly. For the I-405/SR-22 corridor, 7 to 9 runs were collected for each direction along each modeled freeway for each peak hour over a two-day collection period. For the I-5 corridor, 24 travel time samples were collected per travel direction for each peak period over a 3-day period. For the I-205/I-5 corridor, the modeling team further sought to collect 4 travel time samples per hour per direction over multiple weekdays.
- **Field surveys** – Where required, field visits were conducted to collect roadway geometry and traffic signal operations data, identify ITS elements, verify previously collected data, pinpoint locations for manual counts, and identify congestion patterns.
- **Aerial photographs** – Aerial photographs were used to collect information about roadway geometry and, in some cases, to help identify bottleneck locations and the extent of queuing. Depending on the corridor, these analyses have relied on photographs that were already available, photographs that were specifically captured for the project, or photographs from online sources such as Google Earth.
- **Photo logs** – Where needed, existing photo logs were used to help locate roadway elements. This includes photo logs of major roadway sections developed by Caltrans and available through PeMS, as well as high-resolution photo logs developed for Google for its Streetview application.
- **Regional travel demand models** – Regional travel demand models were used to obtain information about traffic flow patterns between defined origin and destination zones. Where possible, O-D flow matrices produced by travel demand models were inputted as seed matrices in the traffic simulation models. These matrices were then subsequently manipulated to produce flows better matching observed vehicle counts or to develop a series of hourly matrices capturing the observed changes in traffic patterns across a peak travel period.
- **Signal timing plans** – Where possible, **s**ignal timing plans for arterial intersections and metered freeway ramps were obtained from the agency responsible for the operation of the traffic

control devices. Where existing timing plans could not be retrieved, surrogate plans were developed either based on field observations or using the Synchro signal optimization software.

- **Transit information** – Where required, information about transit routes and schedules were obtained from the agencies operating the services being modeled.
- **Previous studies** – Some modeling efforts used data that had been collected through other projects. Information obtained this way includes data describing regional vehicle fleet composition, vehicle occupancy rates, and general driver behavior.

The development of simulation models using the macroscopic FREQ 12 model generally required fewer data than microscopic models using Paramics, VISSIM, TransModeler and CORSIM. This often translated into lower data collection costs. In some cases, the costs savings allowed to make additional investments towards data collection. As an example, the light input data requirements imposed by FREQ 12 allowed the US-101 modeling team to use available resources to simultaneously count vehicular flows on all ramps along the corridor while simultaneously measuring mainline performance with aerial photography to spot the starting times, durations, and extent of queuing over the entire freeway. This provided a more extensive dataset for the validation and calibration of the developed model that would have been possible if a microscopic or mesoscopic model had been used.

5.5. DATA VALIDATION

Data validation can help safeguard against the use of erroneous data and/or significant outliers in the development or calibration of a simulation model. While calibration can partially compensate for erroneous data, the utilization of erroneous data to support model calibration can only lead to an inaccurate representation of reality. While project documents generally provide little information on data validations activities, there is evidence that some data checks were conducted:

- **US-101 San Mateo Corridor** – Project documents suggest that counts from various PeMS stations were compared to assess their consistency. This comparison revealed that the station at the southern end of the corridor produced unusually low counts when compared to the others. This led the modeling team to replace this erroneous data with data from adjacent stations. While field surveys further revealed that construction activities along the corridor had likely affected some of the travel time probe vehicle runs, no attempt was apparently made to replace this affected data.
- **I-205/I-5 San Joaquin** – Project documents indicate that many inconsistencies were found with the data collected from PeMS stations, Census counts, average vehicle occupancy counts, ramp tube counts, and manual vehicle classification counts. With Caltrans approval, average freeway mainline PeMS data from October 2008 were used as the primary source of information for model development. Ramp counts showing inconsistencies with the reference PeMS data were then adjusted to match the reference mainline flows.
- **I-405/SR-22 Orange County** – Traffic volumes extracted from PeMS were checked for consistency across successive monitoring stations and against manual traffic counts. This analysis resulted in the flagging, and occasional removal, of count data that caused unrealistic differences in traffic volumes between adjacent PeMS stations.

5.6. DEMAND MODELING

Traffic demand was generally modeled in the form of O-D flow matrices. The only two exceptions were for the US-101 and I-205/I-5 corridors. In the first case, FREQ 12 only allowed the demand to be defined as flow volumes at network entry and exit points. Flow rates on individual segments along the freeway were then reconstructed based on the provided entry and exit flow rates. In the second case, CORSIM only allowed an O-D flow matrix to be developed for freeway. Vehicle movements on arterials were simulated by stochastically assigning a turn movement to vehicles at each encountered intersection.

The remainder of this section provides more information about the following aspects of traffic demand modeling:

- Evaluation horizons;
- Evaluation periods;
- Demand intervals;
- Vehicle types;
- Development of base year O-D matrix; and
- Development of horizon year O-D matrix.

5.6.1. EVALUATION HORIZONS

Table 25 presents the evaluation periods that were considered for each corridor. As can be observed, all corridors sought to evaluate both current corridor operations and operations at some point into the future. The modeling of current operations generally sought to reproduce recently observed traffic conditions. Depending on when the modeling effort was initiated, and period covered by the available data, the base year was typically set to correspond to a year between 2005 and 2009. From the base year, network operations were then evaluated at one or two points into the future:

- **Near-term horizon –** Evaluation of corridor operations five of six years beyond the base year, typically at a year corresponding to 2014 or 2015. This horizon was typically considered to evaluate improvements projects that could realistically be delivered in five or six years when factoring the time needed for design, environmental assessment, approval, and deployment.
- **Medium-term to long-term horizon** – Evaluation of projects that could be delivered between 2020, and 2030.

Table 25 – Evaluation Periods and Horizons Considered

Corridor	Base Year	Horizon Year(s)	Days of Week Considered	Time of Day Considered	AM Peak Boundaries	PM Peak Boundaries
I-80 West	2005	2015, 2035*	Typical weekday	Peak periods only	5:00 – 10:00	2:00 – 7:00
US-101 San Mateo	2009	2015, 2030	Typical weekday	Peak periods only	6:00 – 10:00	2:30 – 7:30
I-5 Los Angeles	2007	2020	Typical weekday	Peak periods only	6:00 – 9:00	3:00 – 7:00
I-205 / I-5	2009	2014, 2024	Typical weekday	Peak periods only	5:00 – 10:00	2:00 – 7:00
I-805	2006	2020	Typical weekday	Peak periods only	6:00 – 9:00	3:00 – 7:00
SR-22 / I-405	2008	2020	Typical weekday	Peak periods only	5:00 – 10:00	2:00 – 7:00

* Evaluations not conducted with developed traffic simulation model

While long-term evaluations were conducted for all corridors, only three corridors performed near-term evaluations. For the three corridors with near-term evaluations, long-term evaluations focused on network operations 10, 15 or 20 years beyond the near-term horizon. For the three corridors that did not consider a near-term horizon, the long-term evaluations all focused on a 2020 horizon year. This roughly placed the evaluations 22 to 24 years beyond the base year.

Within each corridor, the selection of the horizon years was largely influenced by regional transportation planning documents, as travel demand patterns from these models were usually used as input for the demand modeling. For instance, the 2024 horizon for the I-205 corridor drew information from the 2023 regional demand planning model. Similarly, the 2020 horizon for the I-805 corridor corresponds to the horizon year modeled within the SANDAG regional travel demand model. For the I-405/SR-22 corridor, a 2020 horizon was selected while the regional OCTA travel demand model considered a 2030 horizon based on the assessment that microscopic simulation models may not be suited for evaluations that far into the future. The same argument was invoked to justify the disuse of simulation to assess corridor operations along the I-80 corridor over the 2035 horizon. Since high levels of congestion were forecasted to exist by 2035 without significant network expansion, it was argued that microscopic simulation could not accurately assess traffic behavior along the corridor, even with a calibrated model.

5.6.2. EVALUATION PERIODS

In addition to developing traffic demand patterns for a base year and one or two horizon years, separate patterns were developed to cover the AM peak and PM peak periods. Evaluations typically focused on peak weekday travel periods, since most operational problems occur within these periods. As shown in Table 25, relatively consistent boundaries were used for the definition of the AM and PM peak periods across all corridors. The AM peak period is typically assumed to start at 5:00 or 6:00 AM and end at either 9:00 or 10:00 AM. Similarly, the PM peak period is assumed to start at 2:00 or 3:00 PM and end at 7:00 PM.

Table 26 – Modeled Traffic Demand Elements

Corridor	Model	Demand Interval	Vehicle Types				O-D Flow Modeling
			SOV Car	HOV Car	Trucks	Buses	
I-80 West	Paramics	1 hour	●	●	●	●	• Combined O-D matrix for SOV cars and trucks • Combined O-D matrix for HOV cars and buses
US-101	FREQ 12	1 hour	●	●	●		• Combined O-D matrix for passenger cars, trucks and HOV vehicles
I-5 Los Angeles	VISSIM	1 hour	●	●	●		• Separate O-D matrices for passenger cars, trucks and HOV vehicles
I-205/I-5	CORSIM	1 hour	●	●	●		• O-D matrices defined only for freeways • Combined matrix for passenger cars and HOV vehicles; separate matrix for trucks • Arterial flows defined by network entry flows and intersection turn percentages
I-805	TransModeler	15 minutes	●	●	●		• Separate O-D matrix for each vehicle type
I-405/SR-22	Paramics	1 hour, with 5-minute flow profiles	●	●	●		• Combined O-D matrix for cars and trucks • Separate matrix for HOV vehicles

5.6.3. DEMAND INTERVALS

As indicated in Table 26, flow patterns were typically developed for each simulation hour. For most corridors, this meant that the simulated traffic flow patterns remained constant within each hour and only changed when switching from one period to the next. The I-805 and I-405/SR-22 corridors are the only two using a more refined modeling approach. For the I-805 corridor, 15-minute flow patterns were developed. For the I-405/SR-22 corridor, an optional demand profile was developed within Paramics to adjust every 5 minutes the rate at which vehicles are released onto each network. While 15-minute demand intervals were also considered for the US-101 corridor, this approach was eventually abandoned in favor of an hourly-based modeling approach to reflect the fact that the corridor's traffic demand data were derived from hourly counts.

5.6.4. VEHICLE FLEET MODELING

All the reviewed corridors modeled the movements of single-occupancy passenger cars (SOVs), high-occupancy passenger cars (HOVs) and trucks. Buses were explicitly modeled only for the I-80 corridor, but only partially. While buses were released according to published schedules, bus stops were not coded. The intent was not to assess the impacts of improvements on transit ridership, but rather to simulate how transit vehicles utilize HOV lanes along the freeway.

Depending on the corridor, the demand modeling resulted either in the development of a single O-D matrix representing the movements of all vehicles or the development of multiple matrices representing specific groups of vehicles. In most cases, classification counts that had been conducted by Caltrans or the regional planning organization prior to the start of the modeling project were used as the basis for dividing the total traffic demand into vehicle-specific flow patterns. The US-101 corridor is the only one for which field data collection efforts were conducted to capture vehicle fleet patterns.

5.6.5. BASE YEAR O-D MATRIX DEVELOPMENT

The following subsections detail activities that were conducted to develop travel demand patterns for the modeling of existing conditions. The most common approach involved using forecasts from a regional travel demand model to estimate the number of trips entering and exiting the study corridor during a given day or peak period. Adjustments were then made to disaggregate the resulting daily or peak-period trip patterns into hourly patterns. The resulting hourly O-D flow matrices were in turn further refined using custom or simulation-based tools to enable the modeled flow patterns to closely replicate individual traffic counts from the reference period across the corridor. In some cases, manual adjustments were also made during the model calibration to ensure an adequate replication of bottlenecks.

I-80 West

For the development of 2005 base year traffic along the I-80 corridor, the 2005 Countywide Travel Demand Model used by the Alameda County Congestion Management Agency (ACCMA) was used as a starting point. This model was selected instead of the one maintained by the Metropolitan Transportation Commission (MTC) based on the fact that it already modeled the project's target 2015 horizon year. It also featured a more detailed road network within the highly-congested western portion of the corridor.

Figure 42 illustrates the process that was followed to develop the base year travel demand. A particular problem with the ACCMA model was that it had been validated only for use within Alameda County. However, a portion of the corridor extended into neighboring Contra Costa County. To address this problem, land uses within the portion of the ACCMA model covering relevant sections of Costa Contra County were revised to be consistent with the countywide travel model that was then used by the Contra Costa Transportation Authority (CCTA). Changes were also made to the modeled roadway network within Alameda County to better reflect existing conditions.

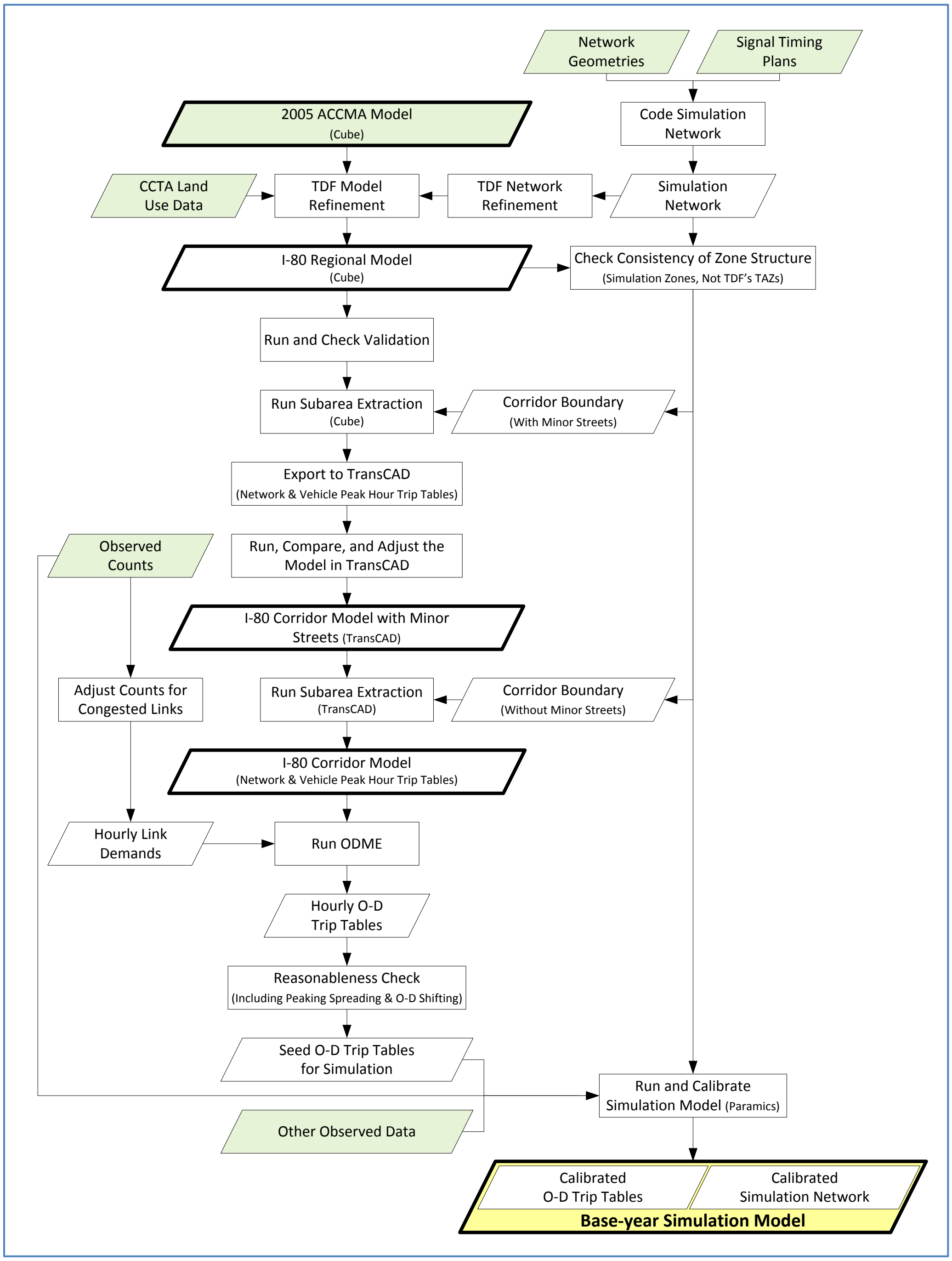


Figure 42 – Base Year Travel Demand Estimation Process for I-80 West Corridor

After completing the changes, a subarea matching the limits of the traffic simulation model was extracted from the Cube model and imported into the TransCAD model. The TransCAD model was then used to generate O-D trip tables for the simulation network for each simulation hour. The resulting tables were in turn inputted into Paramics, and subsequently adjusted using calibration functions available within the software to allow them to better reflect observed traffic counts along the corridor.

The demand estimation process resulted in the development of two set of hourly O-D matrices. A first set described the combined movements single occupancy vehicles and trucks, while a second set described the combined movements of high occupancy vehicles and buses. To distinguish between vehicle types within each matrix, average proportions of vehicle types were developed based on data compiled by Caltrans and from other sources and coded within Paramics. This allowed Paramics to stochastically assigning a type to each generated vehicle based on a given proportion of vehicle types. As an example, 10% of all the trips generated from the HOV/bus matrix were assumed to be made by buses, while the remaining 90% of trip were assumed to be trucks.

US-101 San Mateo

Traffic demand for the US-101 corridor was developed exclusively from freeway mainline PeMS data, manual mainline occupancy counts, and 24-hour ramp tube counts that were collected from the various entry and exit points along the modeled freeway. This data allowed FREQ 12 to generate flow rates between each entry and exit point replicating observed counts. The demand estimation process was repeated for each hour to be simulated. While this process provided for the development of an O-D flow matrix for the freeway, it should be emphasized that unlike microscopic or mesoscopic simulation models, this matrix is not used to determine the movements of individual vehicles, but simply to calculate the resulting flow rate on individual links. There are no adjustments to the O-D flows unless there is an adjustment to the entry and exit volumes provided as input.

The O-D matrices developed by FREQ 12 defined the movements made by all types of vehicles confounded. To represent truck movements, it was assumed that 4% of all vehicles traveling along the corridor were trucks. Vehicle occupancy factors were subsequently developed based on observations conducted at three locations along the corridor and occupancy data from Caltrans. Section-specific vehicle occupancy factors were then developed using the collected data and entered into FREQ 12.

I-5 North and I-5 South, Los Angeles

The Caltrans version of the SCAG regional travel demand model was used to develop the travel demands for the I-5 North and South VISSIM models. The travel demand model was used in an initial step to produce a first estimate of trips traversing the area covering by each freeway section. Two sets of adjustments were then made to allow the resulting trip matrices to better match observed flow data:

- The total flows entering and exiting the traffic zones at network boundaries were first adjusted to match available traffic counts at origin and destination locations. This was accomplished using Excel macros designed to perform incremental adjustments on O-D matrix cells based on the average of the row and column adjustments.
- Individual O-D cell values where adjusted in a second step to obtain a better match to available traffic counts on freeway ramps. O-D flows were first adjusted to match observed on-ramp flows, and then adjusted to match off-ramp flows. This process typically only required 5 iterations to obtain convergence between the sums of O/D pairs and the ramp traffic counts.

Following the above adjustments, the resulting O-D flows were inputted into VISSIM. Further adjustments were then made to the O-D flow matrices during the calibration process to reduce differences between simulated and observed link volumes at origin and destination nodes, as well as to better replicate bottlenecks. Adjustments were primarily made at mainline freeway locations and at system interchanges. They resulted in changes that only modified O-D cell values by 5% or less.

Upon completing the O-D flow matrix development, specific matrices representing the movements of passenger cars, trucks and high-occupancy vehicles were finally extracted from the general flow matrix using truck percentages derived from flow counts and data from traffic sensors located on HOV lanes.

I-205/I-5 San Joaquin

Unlike other simulation models, CORSIM uses two processes to model traffic demand across networks combining freeways and arterials. This is due to the use of different models for simulating traffic movements: FRESIM for freeways and NETSIM for arterials. Freeway demand is modeled by defining for each on-ramp the percentage of vehicles traveling to each downstream off-ramp or freeway mainline exit point. In essence, this process defines an O-D matrix for freeway traffic. For the arterials, traffic movements are defined using intersection turn percentages. Vehicles are not assigned to travel from a specific origin to a specific destination, but rather to move through the network based on stochastic choices made at individual intersections. This reliance on two models prevents CORSIM from dynamically shifting traffic between freeways and arterials in response to changing conditions.

Modeling of the base year traffic demand relied primarily on observed traffic counts:

- Freeway hourly O-D flow matrices were developed using available freeway mainline and ramp counts ranging from 2005 and 2009, with average PeMS mainline flow data from October 2008 used as the primary source of information. The matrices were developed using an O-D matrix estimation procedure that incrementally adjusts the flows assigned to individual cells within the O-D matrix with the goal of minimizing the differences between observed and calculated flow rates at count locations.
- Turning splits for major intersections were derived from 2-hour turning counts conducted in November 2008, December 2008 and January 2009 during both the AM and PM period, as well as 24-hour arterial counts that were conducted between May 2007 and December 2008. Volumes for the other hours of the evaluation period were estimated by analyzing temporal aspects from the collected data.
- Turning splits for minor intersections were inferred by analyzing known traffic volumes on nearby arterials and manual count data from a sample of minor intersections across the region. Some of these analyses were also conducted using Synchro/SimTraffic.
- Signal timing plans for intersections lacking timing plan information were generated using Synchro/SimTraffic.

The above process resulted in the development of hourly flow patterns covering trips made by all vehicle types. Manual vehicle classification counts that had been conducted at various locations within the network were then used to develop truck-specific freeway O-D data and intersection split percentages. HOV counts were further considered to define the proportions of passenger cars that should be treated as HOV vehicles within each simulation hour.

I-805 San Diego

Traffic demand for the I-805 corridor was developed from the regional travel demand model. For each simulation hour, the process started with using SANDAG's macroscopic TransCAD regional travel demand model to assign trips to the regional road network and to subsequently extract trips crossing the study corridor. To extract these trips, an approach different to common practice was followed. Zones in the TransCAD model located within the study area were split into smaller zones to accommodate the zonal system coded in TransModeler before running the travel demand model. This allowed the extraction of TransCAD trips that directly matched the zones defined in TransModeler, thus removing the need to manually split trips across zones or manipulate O-D matrices.

Because the travel demand model only produced daily trips, a peak spreading methodology was employed to disaggregate the daily trips into hourly trips. A separate algorithm was also applied to consider the effects of congestion on travel demand before inputting the flow matrices into TransModeler. Within the traffic simulation model, built-in functions were finally used to perform additional adjustments against observed link counts and turning counts.

A final step converted the general O-D flow matrices into vehicle-specific matrices. Passenger-car and truck flow matrices were first estimated using observed truck percentages. Matrices reflecting the movements of single and high occupancy vehicles were subsequently developed from the resulting passenger car matrix by considering O-D mode share data from the SANDAG travel demand model.

I-405/SR-22/I-605 Orange County

Travel demand data for the I-405 and SR-22 corridors were developed from OCTAM's TransCAD travel demand model covering Orange County. Similar to other corridors, the OCTAM model was first cordoned to isolate sections covering the study corridors and then used to develop hourly O-D matrices of trips entering and exiting each corridor during the AM peak and PM peak periods. To match observed turn movements at nodes within the network, the model was also used to generate and assign trips from zones situated within the boundaries of each corridor.

The O-D flow matrices developed from the OCTAM model were subsequently coded in Paramics, where additional adjustments were made to obtain a better match with observed traffic counts across the corridors. These adjustments were made using the O-D estimation tool offered with Paramics. This tool uses simulation to evaluate whether a given O-D matrix result in flows matching observed counts. Where differences are found, incremental adjustments are made to the O-D flows until a reasonable match is found, a set number of iterations are made, or the process is stopped by the user. This process includes the ability to utilize GEH statistics as the primary criterion for developing O-D flows. In this case, adjustments were made to ensure that a GEH of less than 5 was obtained in at least 85% of the cases for the sum of all flows, individual link flows, and intersection turning counts.

For each hour, a single O-D matrix modeled the movements of passenger cars and trucks. However, a separate matrix was developed to model the movements of HOV vehicles. Within the first matrix, trucks were assumed to constitute a certain percentage of traffic based on data from vehicle classification counts that were conducted by Caltrans at two overpasses in 2007.

5.6.6. HORIZON YEAR O-D MATRIX DEVELOPMENT

This section details activities leading to the development travel demand forecasts for future years. Most of the efforts considered information provided by regional travel demand models to estimate traffic growth factors that were then used to convert a base year demand profile into a horizon year profile.

I-80 West

O-D flow matrices for the 2015 horizon were developed using travel projections produced by the modified regional travel demand model described in Section 5.6.5, but with a road network incorporating improvements that had already been accepted and programmed by regional

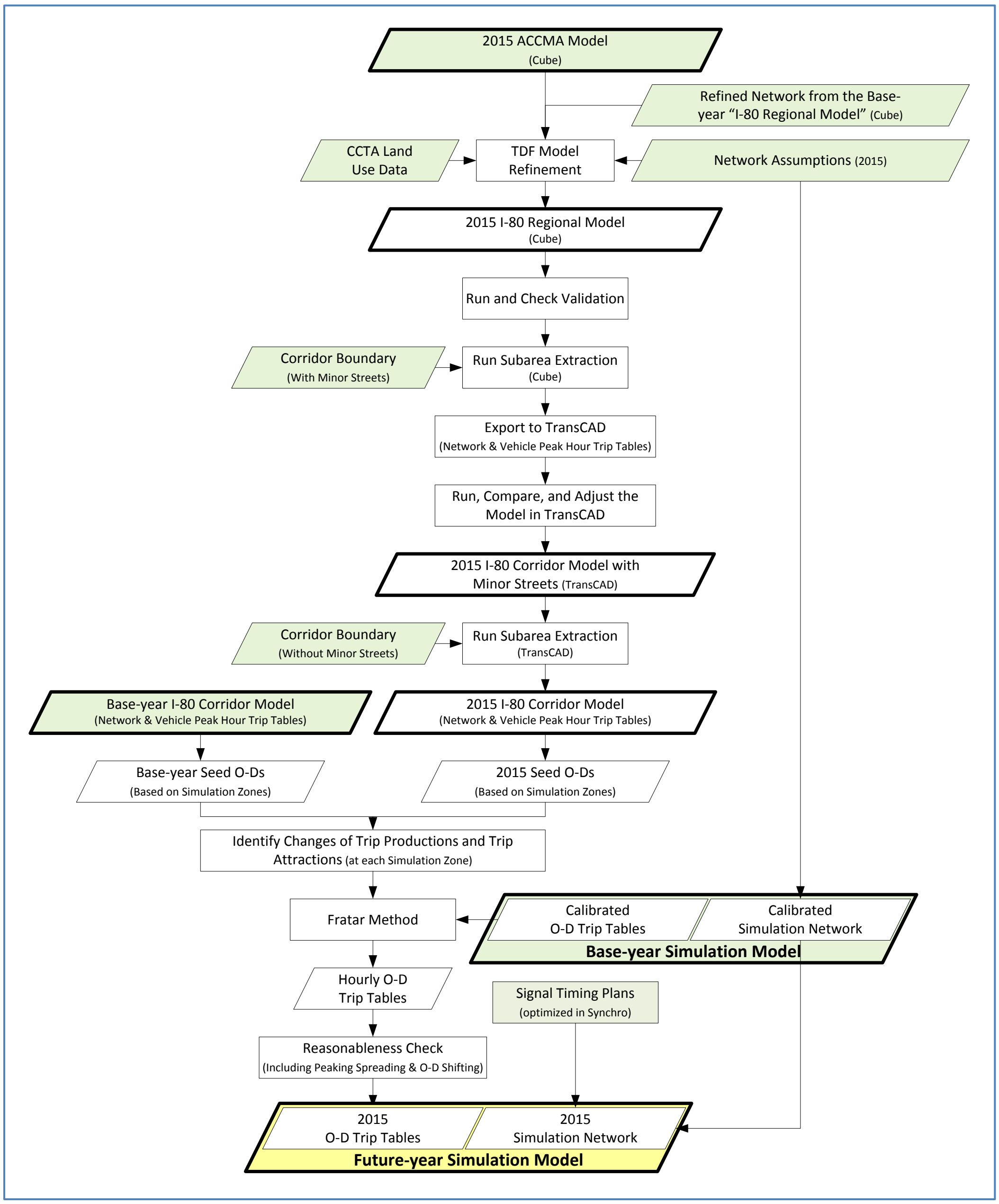


Figure 43 – 2015 Travel Demand Estimation Process for I-80 West Corridor

transportation agencies. Similar to the base year, the ACCMA model was used as the base model from which to predict trip patterns. Within the model, land use for the 2015 horizon was estimated based on the regional ABAG forecast allocations for growth. Land use within the portion of the corridor within Contra Costa County was further updated using data interpolated from the 2010 and 2020 analysis years within the CCTA travel demand model. Figure 43 illustrates in greater detail the process that was used to develop the 2015 demand.

Trip patterns produced by the refined 2015 travel demand model were not directly used within the Paramics simulation. The 2015 travel demand to simulate was determined by using a Fratar-based method. This method added the forecasted growth in travel demand to the 2008 O-D flows using the equation shown below:

$$2015\ Demand = 2008\ Demand + \begin{pmatrix} 2015\ Demand\ Forecast \\ from\ Travel\ Model \end{pmatrix} - \begin{pmatrix} 2008\ Demand\ Forecast \\ from\ Travel\ Model \end{pmatrix}$$

Because the travel demand model only provided growth forecasts for the peak hour, the modeling team also had to develop scale factors enabling them to extract from the peak hour data flow patterns for individual simulation hours. These scale factors were developed based on observed traffic counts by simply computing the ratio of observed trips during a given hour relative to the total number of trips observed during the peak hour.

US-101 San Mateo

Growth forecasts for the year 2015 and year 2030 were developed using the latest version of the San Mateo County Travel Demand model, which offered land use and networks for 2005, 2015, and 2030. Since the intent was to compare the proposed strategies to a "do nothing" baseline, the highway and transit improvements assumed by the City/County Associations of Governments (CCAG) of San Mateo County for the 2015 and 2030 forecast years were stripped down to include only baseline and improvement projects already under construction. However, removed long-term projects were added to the list of improvement strategies being evaluated as part of the CSMP. Following the above adjustments, the CCAG model was re-run for 2015 and 2030 with only the baseline 2015 projects in place, and flow data extracted for use in the FREQ 12 model.

I-5 North and I-5 South, Los Angeles

Development of the 2020 O-D flow matrices relied on the application of growth rates based on regional forecasts. Location-specific growth rates based on data extracted from the regional travel model were applied to the total flow entering and exiting each defined origin and destination zone. A uniform growth factor was not applied to account for the fact that growth rates may not be uniform along the corridor. Most of the applied growth rates imposed flow increases ranging between 0% and 100%. Only a small percentage of O-D pairs had a growth factor greater than 100%, and most negative rates imposed reductions in traffic volume of less than 25%. After applying the local growth rate, the resulting O-D matrices were then checked and balanced.

I-205/I-5 San Joaquin

While existing traffic conditions along the I-205/I-5 corridor were estimated solely based on traffic counts, the county-wide travel demand model used by the San Joaquin Council of Governments (SJCOG) was used to develop suitable travel demand forecasts for 2024. This model was more used to estimate:

- Traffic growth at network entry/exit links;
- Traffic growth on freeway ramps;
- Changes in directional traffic volumes at intersections; and
- Changes in proportion of high-occupancy vehicles.

Simple growth factors were not applied to the 2006 base year demand based on the assumption that unequal growth in land use will likely produce different trip patterns than those observed in 2006. It was also recognized that different congestion levels and the addition of new transportation facilities can further affect future demand levels and trip patterns across the corridor.

The modeling of the 2024 travel demand started with the 2023 land use and road network modeled within the regional travel demand model. Additional network elements were then coded to obtain a model more accurately replicating freeways, interchanges, ramps, and intersections. Link attributes, such as number of lanes and capacities were also updated to reflect planning documents.

A limitation of the SJCOG model was that it could only generate trip forecasts for the peak travel hour. To address this problem, a process was developed to expand peak hour trips into peak period trips using conversion factors based on hourly traffic counts. Additional adjustments were further made to reflect that trips with long travel times may have been shifted out of the peak hour into the shoulder hours.

Using the estimated hourly flows, traffic growth rates for the network entry/exit links and freeway ramps were calculated for each travel hour. Growth was determined by calculating differences between the 2024 and 2006 trip estimates produced by the regional travel model, and using the 2008 peak hour demand that had been estimated from traffic counts as a reference point, as shown in the equation below. Following this calculation, the future traffic demand would then be obtained by simply multiplying the resulting growth rate to the existing year demand.

$$Growth\ Rate = \frac{\left(\begin{matrix}2024\ Peak\ Hour\ Forecast\\ from\ Travel\ Model\end{matrix} - \begin{matrix}2006\ Peak\ Hour\ Forecast\\ from\ Travel\ Model\end{matrix}\right)}{2008\ Peak\ Hour\ Demand} \times 100\%$$

$$\begin{matrix}2024\\ Hourly\ Demand\end{matrix} = \begin{matrix}2008\ Hourly\\ Demand\end{matrix} \times \ (1 + Growth\ Rate)$$

After completing the estimation of the 2024 entry link and freeway ramp flow forecasts, an algorithm was used to develop O-D matrices for each simulation hour reflecting the estimated traffic volumes.

During the calculations, checks were made to ensure the reasonableness of the estimated flows. These checks revealed excessive growth for the 2024 horizon year at the I-205 entry/exit link near the Altamont Pass and I-5 entry/exit link near Sacramento. This excessive growth was found to be caused by three limitations in the SJCOG model:

- The analysis first showed a high percentage of trips exiting the county. While it made sense for home-based work trips to commute outside the County, the majority of trips made for other purposes, such as going to school or shopping, should remain within the county.
- Static ratios were used to estimate mode splits. Transit trips were assumed to correspond to 1% of all trips, while shared rides would account between 0.61% and 0.99% of all trips, depending on the trip purpose. Applying the same factors to both the base and horizon years may have led to ignoring potential increases in transit and shared vehicle use due to increased congestion.

- The third limitation is common to all models designed to analyze the peak hour only. Since the SJCOG model assumes that all trips start and end within the peak hour, increases in travel time due to congestion may result in a significant proportion of trips starting or ending before or after the analysis period.

To address the above problems, the modeling team developed an iterative adjustment algorithm that sought to impose a capacity threshold within the trip tables (for instance, 12,000 vph at the I-205 entry/exit links and 5,000 vph at the I-5 entry/exit link), reassign trips to different destination where needed, and shift a portion of trips from the peak hour to other hours within the peak period. Manual adjustments were also made where deemed necessary.

Adjusting intersection turning splits required using a slightly different approach. Similar to the freeway and ramp flows, the regional travel demand model was used to estimate traffic growth at major intersections along the corridor. A Furness matrix program was then employed to estimate turn proportions from the estimated volumes. Adjustments were also made to ensure consistency with ramp flows and flows between adjacent intersections. For minor intersections, the turning splits that has been estimated for the base year were assumed to remain constant, except where changes were deemed appropriate to provide reasonable consistency in flows between adjacent intersections.

Changes in the proportion of HOV were estimated by simply comparing outputs from the regional travel demand model for the base and future years. Changes in truck percentages were finally estimated using data from a separate truck study.

I-805 San Diego

The development of the 2020 O-D matrices for the I-805 corridor followed the same process as for the base year matrices. For each scenario, trip estimates for the target year were produced by running the regional travel model with a road network incorporating various improvements. Hourly O-D matrices were then produced for each vehicle type using the procedure described in Section 5.6.5 and a formula similar to those that were used for the I-80 and I-205 corridors:

$$\begin{matrix} Future \\ Demand \end{matrix} = \begin{matrix} Base\ Year \\ Demand \end{matrix} + \left(\begin{matrix} Future\ Demand\ Forecast \\ from\ Travel\ Model \end{matrix} - \begin{matrix} Current\ Demand\ Forecast \\ from\ Travel\ Model \end{matrix} \right)$$

I-405/SR-22/I-605 Orange County

Development of the 2020 travel demand data for the I-405/SR-22 corridor followed the same principles as for the development of the base year matrix. Trips across the I-405 and SR-22 corridors were first extracted from the OCTAM travel demand model to produce seed O-D matrices for single occupancy vehicles (SOVs) and high occupancy vehicles (HOVs) for the AM and PM peak periods respectively. Instead of developing entirely new O-D matrices from the OCTAM model, growth factors to be applied to the 2008 base year O-D flow matrices were developed from the travel demand data.

Three specific growth rate methodologies were considered: application of uniform growth rate to all values in the O-D matrices to reflect overall traffic growth across the network; application of growth rates reflecting forecasted growth from each origin zone, and application of individual growth rates to individual O-D cells. Following an analysis of the resulting O-D matrices, if was determined that the best methodology would be to first apply origin-based growth rates and then apply an overall growth rate to adjust flows within individual cells for which excessive growth would be projected.

5.7. ERROR CHECKING

Error checking is where a modeler verifies that the simulation model is built correctly and performs reasonably. This is an important modeling step that should not be overlooked, as coding errors carried through the calibration process can significantly affect simulation results and lead to over-modification of model parameters to compensate for the error.

Error checking usually occurs prior to model calibration and often involves two separate activities:

- Review of model input parameters; and
- Review of simulation animations.

In the first step, parameters modeling network geometry, traffic demand, traffic control devices and driver behavior are reviewed to ensure they provide valid and logical values. In many modeling efforts, this review was aided by various visualization tools offered by the simulation tool being used. As an example, Figure 44 illustrates how the Paramics' Audit Tool can be used to check the consistency of coded link free-flow speeds. The Google Maps application provides another way of checking model accuracy without involving field visits. As an example, Figure 45 illustrates divergences that were uncovered using Google Maps. This example, which is part of a simulation model that has been approved by Caltrans, includes an incorrectly placed side street and an intersection with a missing signal.

A review of animations produced by a simulation tool can further provide insights into the operation of, and interaction between, various simulation elements. An example from the I-5 model review is shown in Figure 46. In this example, a review of animations produced by VISSIM showed a potential problem with how vehicles interacted near a freeway entrance, resulting in artificial congestion. This problem was subsequently corrected.

A general recommendation is to conduct the review in multiple stages using various levels of traffic demand. In a first stage, a model may be run with 10 or 20% of the normal traffic demand. This allows reviewing the behavior of individual vehicles as they traverse the modeled network without being impeded by congestion. Once there is a confirmation that vehicles are behaving satisfactorily, runs may be executed with a higher demand to review how individual vehicles interact with other vehicles. A

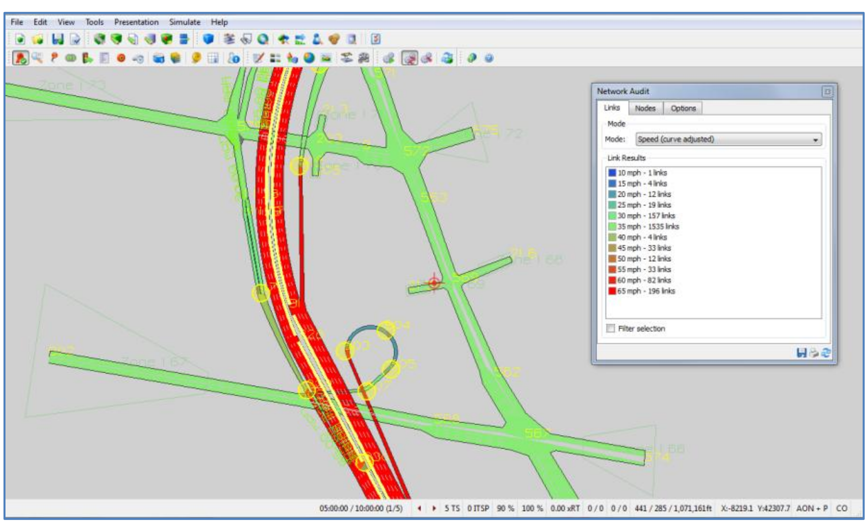


Figure 44 – Review of Network Geometry using Paramics Audit Tool

Figure 45 – Use of Google Maps to Review Geometry Elements

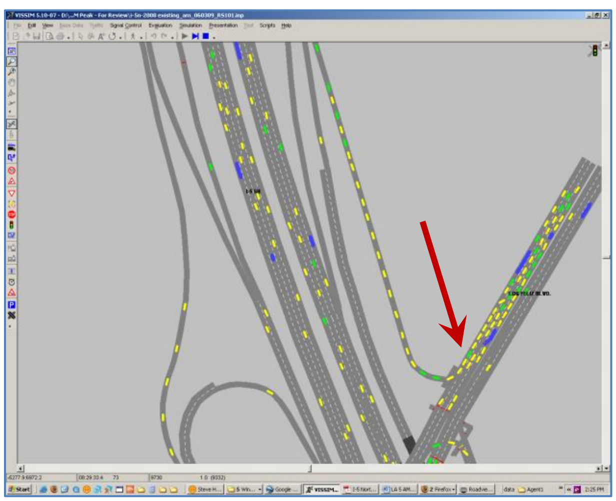


Figure 46 – Example of Potential Coding Error Highlighted by Simulation Animation

frequent recommendation is to utilize either 50% or 60% of the normal traffic demand at this stage, as this demand level is usually high enough to create interactions between vehicles but still low enough to remain congestion-free. Any significant congestion appearing at this level would thus be an indication of potential coding errors.

Phase 1 audit reports, which addressed the initial model review, indicate a varying picture regarding the amount of corrections that needed to be made to submitted models to address geometrical and other technical coding issues. While some networks exhibited very few problems, others had a fair amount of issues. The reasons for this variability are not clear. Expecting that error-free models be submitted for initial review is somewhat unrealistic, given the complexity of the models being developed. However, a realistic expectation is that models without unexplained gross geometrical coding errors be submitted.

A review of the models that were eventually approved by Caltrans revealed a few coding errors that passed through the review process without being flagged. In Figure 47, a freeway link is incorrectly labeled as an urban link. While this error is relatively minor, it could affect how vehicles behave on the link. In Figure 48, inconsistent link types are coded for similar road elements. In this case, the error will not affect vehicle behavior within Paramics, but may affect level-of-service analyses conducted with the software's Analyzer module. Figure 49 illustrates a more serious error. It illustrates the route that vehicles would take to travel from a given origin to a given destination using Paramics' Route Viewer. In this case, a much longer than expected path results from the coding of an inaccurate barred left turn at the last intersection before the destination zone. This error forces vehicles to look for a suitable place to make a U-turn, which artificially increases the flow of vehicles on the nearby arterial links. While this error may have minor impacts in the presence of low vehicular flows, it can have more serious effects in scenarios increasing traffic along the affected arterial.

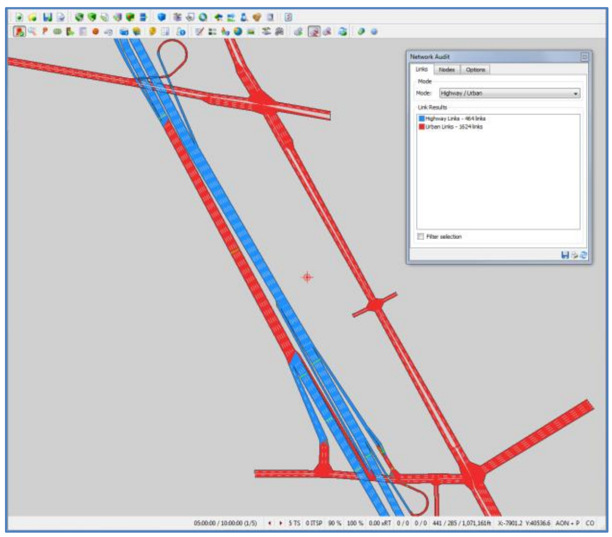


Figure 47 – Paramics Link with Incorrect Urban/Highway Designation

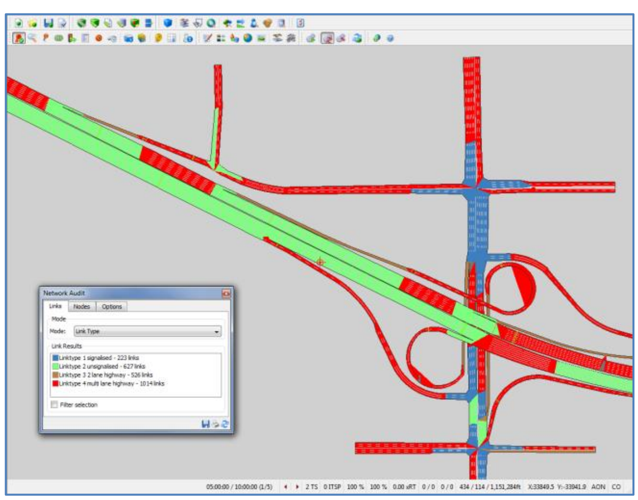


Figure 48 – Paramics Network with Inconsistent Link Type Labeling

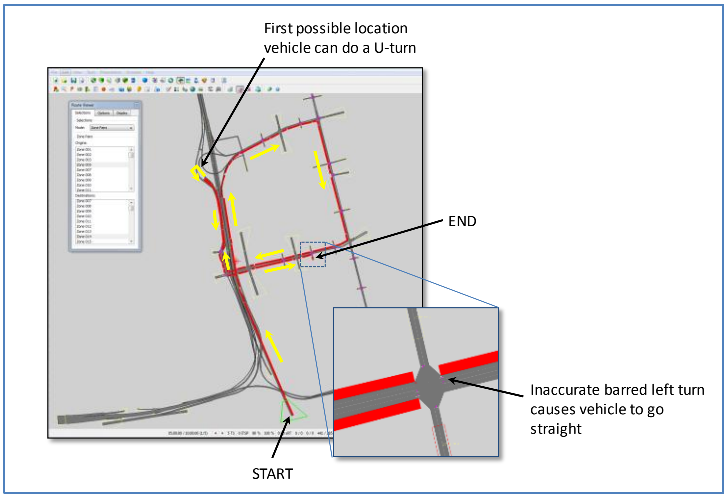


Figure 49 – Effect of Inadequate Modeling of Barred Left Turn

It is recognized that is difficult, if not impossible, to spot all potential errors in large simulation models, particularly errors that may affect a relatively small number of vehicles or the simulation during a narrow time window. It is also recognized that a point may be reached where attempts to resolve remaining errors, particularly minor ones, start to yield relatively minimal benefits relative to the time and resources invested in finding the error. At the corridor planning level, the vast majority of discrepancies do not further necessarily affect the results and conclusions.

The presence of residual errors in some of the approved simulation models, although minor in nature, is an indication that improvements in the review process are needed. For instance, many errors were uncovered using review tools available within the simulation tools. It is possible that individuals who reviewed the model may not have been aware of these tools, particularly if they were not regular users. This emphasizes the need to select reviewers that have the adequate knowledge to review a specific model or have been given adequate training on how to conduct reviews with the model.

5.8. MODEL CALIBRATION

In most reports, the process of calibrating and validating the base year simulation model was noted as the most time consuming and difficult step. After verifying that the coded network contained no basic coding errors, models parameters were typically adjusted to ensure that simulated capacities match observations from the real network. If necessary, trip matrices and route choice parameters were also manipulated to fine tune the simulated traffic demand and obtain realistic patterns. A last step involved the adjustment of model parameters to satisfy target volumes and travel time thresholds. This task often required several iterations, and in some occasions the collection of additional data, until the simulation model was finally approved by Caltrans.

Calibration elements reviewed in the following subsections include:

- Calibration elements;
- Calibration targets;
- Calibration process; and
- Calibration results.

5.8.1. CALIBRATION ITEMS

Table 27 shows the primary model parameters that were adjusted during the calibration process. Comparisons across modeling efforts were made somewhat difficult by the fact that different simulation tools often using different sets of parameters to model driver behavior. Regardless of these differences, the following general observations could be e made:

- For the microscopic modeling efforts, the parameters determining the mean car-following headway, mean driver reaction time, lane-changing behavior, and gap acceptance behavior were the primary calibration parameters.
- For the FREQ 12 macroscopic modeling effort, the main calibration parameter was the capacity of freeway sections.
- Adjusting route selection parameters was only required for the models offering alternate routing possibilities. This included the I-80, I-805, and I-405/SR-22 models. While the I-205 model included parallel arterials, CORSIM did not allow vehicles to select their path due to the use of separate models for simulating traffic on freeways and arterials, as was explained in Section 5.6.5.

Table 27 – Calibration Items

Corridor	Model	Driver Behavior / Roadway performance	Route Selection	Control Devices	Demand Modeling
I-80 West	Paramics	• Mean headway • Mean reaction time	• Global route cost calculation factors • Freeway/arterial cost weight factors	*No reported adjustments*	• Flows between specific origin and destinations
US-101	FREQ 12	• Capacity of freeway sections	*No alternate routes modeled*	*No reported adjustments*	*No reported adjustments*
I-5 North and I-5 South	VISSIM	• Car following parameters • Parameters affecting lane change behavior • Speed distributions	*No alternate routes modeled*	• Intersection signal timings (to calibrate queues at intersections)	• Local adjustments to balance demand and assign volumes on individual links
I-205 / I-5	CORSIM	• Global car-following sensitivity parameters • Mean discharge headway (ramps) • Gap acceptance distribution (at stop signs) • Lane bias • Truck turn multipliers	*No route selection possible*	• Intersection signal timings (to reduce left-turn queuing at intersections)	*No reported adjustments*
I-805	TransModeler	• Critical headways • Gap acceptance • Lane changing look-ahead • Speed thresholds for yielding	• Path influence factors • Routing cost model • Route selection model	• Ramp metering rates (to improve operations under high volumes)	*No reported adjustments*
I-405/SR-22	Paramics	• Mean headway • Mean reaction time • Force merge behavior at intersections • Next lane definitions • Signposting range	• Global route cost calculation factors • Link-specific and link types cost factors • Dynamic feedback • Driver familiarity with network	*No reported adjustments*	*No reported adjustments*

- Traffic signal control parameters were changed in a few cases to address operational problems. For instance, signal timings were changed to reduce unusually long left-turn queues developing at some intersections. In another example, freeway ramp metering rates were adjusted to improve the handling of large traffic flow volumes produced by the simulation. Various reasons can be invoked for rationalizing such changes, such as the use of estimated timings to model vehicle-actuated systems, use of outdated signal timing plan data, or difficulty of calibrating complex or aggressive gap-acceptance behavior at intersections. Often, an increase in green duration by an amount as small as 2 seconds can be sufficient to significantly reduce queuing problems. At many intersections, changing the signal timing parameters may thus have been viewed as the most effective option to quickly resolve operational problems.
- Adjustments to demand modeling parameters are only reported for the I-80 and I-5 corridors. In these cases, the adjustments were made to fine-tune the replication of bottlenecks and only resulted in modification of less than 5% to the O-D flows that were developed during the demand modeling process.

5.8.2. CALIBRATION TARGETS

All modeling efforts considered calibration targets similar to those described in FHWA's *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Software* and Caltrans' *Guidelines for Applying Traffic Microsimulation Software* documents.

Table 28 compiles the targets that were specifically considered for the reviewed corridors. While additional criteria may have been used internally by the various modeling teams, only the criteria reported in published documents are listed here. The following observations can be made from the tabulated data:

- Calibration targets were typically assessed for each modeled hour.
- For all corridors, the primary calibration goals were to replicate observed link flows, travel times across successive segments or over the entire network, and the location and extent of bottlenecks.
- All modeling teams sought to develop models in which simulated flows on individual links would be within 15% of observed flows for links carrying between 700 and 2700 vph, with a higher error tolerance for links carrying less than 700 vph and a lower tolerance for links carrying more than 2700 vph.
- A GEH of less than 5 was typically sought for individual link flows, except for the I-5 North and South corridors in Los Angeles County, for which a GEH of 6 was used based upon a request from the modeling team and subsequent approval by Caltrans.
- All modeling teams compared the sum of all link flows. In most cases, the calibration simply sought to achieve a difference of less than 5%. For the I-405/SR-22 corridor, the objective was instead to have a GEH value below a given threshold. This is the only corridor to look at this statistic. On the use of the GEH statistic, the modelers for the I-205 corridor argued that using a network-wide GEH flow criterion was not meaningful since the ability to satisfy this criterion is a function of the number of links within the network. For instance, simply splitting a link into two increases the sum of volumes, which then reduces the acceptable difference between the observed and simulated flows, thus enabling the GEH criterion to be met.

Table 28 – Calibration Targets Considered in Reviewed CSMP Corridors

Calibration Criteria	Acceptance Target	I-80 West	US-101	I-5 North / I-5 South	I-205 \ I-5	I-805	I-405/SR-22/
Modeled vs. Observed Flows							
Individual link flows							
• Within 100 vph if flow < 700 vph	> 85% of cases	●		●	●	●	●
• Within 15% if flow > 700 and < 2700 vph	> 85% of cases	●		●	●	●	●
• Within 400 vph if flow > 2700 vph	> 85% of cases	●		●	●	●	●
• GEH statistic < 5	> 85% of cases	●			●	●	●
• GEH statistic < 6	> 85% of cases			●			
Turning counts							
• GEH statistic < 5	> 85% of cases						●
Sum of all link flows							
• Within 5%	All accepting links			●	●	●	
• GEH statistic < 4	All accepting links						●
Modeled vs. Observed Travel Times							
Corridor travel times							
• Within 15% or 1 minute, whichever is higher	> 85% of cases	●	●	●		●	
Segment travel times / speeds							
• Within 15% or 1 minute, whichever is higher	> 85% of cases			●	●	●	●
• Speeds within 15%	> 85% of cases				●		
• Speed from model median within range of Measured speeds	All segments				●		
Visual Audits							
Individual link speeds:							
• Visually acceptable speed-flow relationships	To analyst's satisfaction			●		●	●
Bottlenecks:							
• Visually acceptable queuing	To analyst's satisfaction	●	●	●	●	●	●

- A note regarding the sum of all link flows calibration criterion is that this criterion was initially intended to be the sum of flows across a screen line, not the total of all links in a model. The confusion stems from how the criterion has been labeled in the FHWA and Caltrans reference documents. The Wisconsin DOT recently modified its calibration guidelines to clarify that the sum refers to the total flow across screen lines.
- Calibration of the US-101 corridor only considered bottlenecks and travel times. This effort sought specifically to correctly replicate the location of every bottleneck along the corridor, their start and end times within plus or minus one interval, and their maximum length. For the travel times, the focus was simply to match as best as possible the average simulated corridor travel times to the observed travel times within each one-hour period.
- The I-405/SR-22 corridor is the only one listing intersection turning counts as a calibration criterion. This lack of consideration in other modeling efforts is likely due to the fact that the calibration of turn percentages at intersections is not listed as a calibration target in the

Caltrans/FHWA guidelines. However, this criterion is now part of the revised Wisconsin DOT guidelines. While calibrating the link volumes ensures that the total flow on intersection approaches match observations, it does not ensure that turn proportions are adequately replicated. Not calibrating turn movements can lead to simulating turning flows not matching signal timing plans, thus resulting in inaccurate intersection operations and artificial congestion.

- While all modeling teams evaluated travel times, this evaluation was not consistent across all efforts. Some teams have evaluated travel times on a segment-by-segment basis, such as between interchanges, while others only evaluated end-to-end corridor travel times.
- The I-205/I-5 corridor is the only one for which explicit calibration targets for average link speeds were considered. Elsewhere, link speeds were qualitatively evaluated through simple visual audits of speed profiles.
- All modeling teams evaluated the ability to replicate bottlenecks by comparing speed contour plots generated from simulated data against plots that had been previously developed, typically from the corridor’s Comprehensive Performance Assessment.

While the use of a different GEH calibration criterion for the I-5 corridor appears to be a deviation from standard practice, it must be noted that the FHWA and Caltrans guidelines do not formally impose the use of the listed calibration targets. These criteria were initially developed by the Wisconsin DOT for the modeling of the Milwaukee freeway system, and are themselves based on previously developed criteria for travel demand modeling in the United Kingdom. The targets are only provided as examples of potential stopping points. The FHWA guidelines notably indicate that project-specific targets should be developed based on minimum performance requirements for the simulation model, with due consideration of available resources. The targets can therefore vary from project to project. For the I-5 corridor, a GEH value of 6 was adopted based on discussions with Caltrans, as well as prior calibration work along the corridor, to address the high-volume and high-congestion nature of the corridor.

5.8.3. CALIBRATION PROCESS

Due to the interdependence of many model parameters, calibration is typically an iterative process. While individual modeling teams may follow their own processes, often based on prior modeling experience, the processes that were followed for the modeling of CSMP corridors generally appear to have followed the principles outlined in the Caltrans and FHWA guidelines. These principles suggest that global simulation parameters be adjusted first, followed by the local parameters. Project documents further suggest that calibration efforts have generally first focused on adjusting traffic volumes before attempting to calibrate travel times and subsequently moving to bottlenecks.

As indicated in Section 5.8.1, the calibration of route selection algorithms was a necessary additional step only for the corridor with route choices. These only included the I-405/SR-22, I-80 and I-805 corridors. Below is a description of the calibration procedures that were considered for each corridor:

- A two-step calibration process was used for the I-405/SR-22 corridor. In the first step, the realism of routes selected by vehicles was reviewed using the graphical tools offered by Paramics. Where required, the model parameters were changed to resolve erroneous path choices. The second step focused on running the simulation model with different seed values to check the consistency and stability of routes selected between major O-D pairs.

- For the I-805 corridor, tests were made to evaluate the realism of routes selected by individual vehicles under the various routing options offered by TransModeler. However, project documents provide no explicit description of the process that was followed to calibrate the route selection parameter under the retained option.
- For the I-80 corridor, no explicit route calibration process is detailed. The modeling reports simply indicate that route selection patterns within Paramics were reviewed for consistency with observed traffic flow patterns.

While the I-205/I-5 corridor also modeled arterials running parallel to the freeways being evaluated, route selection calibration was not necessary due to the fact that CORSIM uses separate models to simulate traffic on freeways and arterials, as explained in Section 5.6.5.

5.8.4. CALIBRATION RESULTS

Table 29 provides a general review of how well individual models satisfied the established calibration criteria. While the reviewed data shows that no modeling team was able to develop a model fully satisfying all the criteria considered, this was expected given that simulation models never perfectly replicate reality. In particular, the attempts to model relatively long corridors made the calibration efforts significantly more complex.

The following subsections provide general assessments of the degree to which each of the calibration targets listed in Table 28 were achieved for the various corridors.

Link Volumes

Across all corridors, modeling teams were reasonably successful in obtaining individual link flows falling within 15% of observed flows in at least 85% of the cases within each simulation hour. Where the target was not met, it was generally missed by only a few percentage points or for a single hour. The only exception was the for I-5 North model, for which the flow target is more consistently missed. Volume calibration variations for this model were linked to high congestion levels. Based on prior modeling experience with congested networks, the modeling team requested a relaxation of the calibration targets. Upon review of the request, Caltrans allowed model calibration against a GEH target of 6 instead of 5. This resulted in a better satisfaction of the calibration criteria.

Route Selection

While route selection was not an explicit calibration target, this behavioral aspect required verification for all corridors offering alternative routes between origin and destination zones. As mentioned previously, this only concerned the modeling for the I-805, I-405/SR-22 and I-80 corridors.

For the I-80 corridor, Paramics' default link cost model was changed from a model considering only travel times to a model equally weighting travel time and distance. Cost weight factors associated with specific link types were further adjusted to bias route choice towards freeways, while cost perturbations were maintained to replicate the fact that drivers often do not have a perfect knowledge of traffic conditions. While there was an initial attempt to calibrate the model with the dynamic route assignment option enabled, the modeling team was unable to approach the calibration targets within a reasonable amount of time. It was therefore proposed to conduct route diversion evaluations using the

Table 29 – Assessment of Calibration Results

Corridor	Model	Volumes	Corridor Travel Times	Segment Travel Times/Speeds	Bottlenecks
I-80 West	Paramics	Generally within calibration targets.	• Average network travel times within targets.	*Comparisons not provided*	• Small differences in location reported. • Duration generally consistent with observations.
US-101	FREQ 12	*Not explicitly calibrated*	• Calibrated travel times exhibiting differences ranging between 1.8% and 30.5%.	*Not explicitly calibrated*	• Major southbound bottlenecks generally replicated, with some differences in spatial and time extent of bottlenecks. • One major northbound bottleneck replicated, but with some differences elsewhere attributed to non-recurring congestion due to construction effects presents in the floating car data used for validation.
I-5 North	VISSIM	• AM peak volume and GEH targets achieved in about half the cases. • PM peak volume target consistently not achieved for links carrying between 700 and 2700 vph, but GEH target generally met. • Systematic slight over or under estimation of flows often observed along corridor.	• Generally within target during AM peak, except between 8 and 9 AM southbound (-22% difference). • Generally within target during PM, except between 5 and 7 PM northbound (-17% and 34% difference).	• Within target in 64% of cases for AM peak; with differences of 20-40% observed. • Within target in 57% of cases for PM peak; with differences of 20-60% observed.	• Major AM peak bottleneck replicated (only one bottleneck in period). • Generally good replication of bottlenecks during PM peak.
I-5 South	VISSIM	• AM peak volumes and GEH targets achieved in all cases under the revised calibration guidelines accepted by Caltrans. • PM peak volume targets achieved in 15 out of 16 cases (94%); GEH targets achieved in 2 out of 4 cases (50%). • Systematic slight over or under estimation of flows often observed along corridor.	• AM peak model outside range (22-28% difference) for northbound travel, but within range for southbound. • Generally within target in both directions for PM peak.	• Within target in 40% of cases for AM peak model; with differences of 20-30% frequently observed. • PM peak model within target in 45% of cases; with differences of 20-30% frequently observed.	• Major bottlenecks replicated in both the AM and PM peak models; some minor differences observed in time and spatial extension.

Table 29 – General Assessment of Calibration Results (cont'd)

Corridor	Model	Volumes	Corridor Travel Times	Segment Travel Times/Speeds	Bottlenecks
I-205 & I-5	CORSIM	• Volume and GEH targets generally met for freeway and ramp volumes. • Significant differences only for I-5 portion of network between 6 and 7 PM. • Target achieved for arterial links in AM peak but missed for PM peak (19% of links with volumes or GEH outside target range)	*Corridor-wide travel times not assessed*	• 87% of interchange-to-interchange travel time within target for AM peak model. • 71% of interchange-to-interchange travel times within target for PM peak model. • Significant deviations in speed for Eastbound I-205 during AM and PM peak, as well as Northbound I-5 during PM; Differences generally within range of observations, but close to field min.	• Location of major recurring bottlenecks replicated; extent corresponding to median observation. • Other bottlenecks hard to replicate since they vary in location and extent.
I-805	TransModeler	• Calibration targets met for all links.	• Calibration targets met for all AM peak hours, except 7-8 AM (difference of 10.4 min, or 23%). • Corridor target met for all PM peak hours (maximum difference of 2.9 min, or 8%).	• Corridor profile generally matching observations, but with notable differences (20-35%) on many segments. • Target missed in 50% of segment in most simulation hours for both AM and PM models.	• Adequate bottleneck locations for AM peak model, with minor differences in spatial and time extents of bottlenecks. • Some difference in southbound direction for PM peak model. • Northbound bottlenecks adequately located, with minor time and spatial differences.
I-405	Paramics	• Volume targets generally met for links carrying less than 700 and more than 2700 vph. Target met for 68% to 83% of links carrying between 700 and 2700 vph. • GEH statistics generally within target.	*Corridor-wide travel times not assessed*	• 81% and 86% of segment travel times within 15% or one minute during AM peak and PM peak period respectively (as per requirements). • 63% to 98% of segment travel times within target during individual AM peak hours, and 71% to 93% of segments during PM peak hours. • Reference tachometric runs characterized lane-specific conditions that may not reflect the modeled average link behavior.	• Speed contour plots indicate good replication of location of front end of bottlenecks.
SR-22	Paramics	• Volume targets generally met. • GEH statistics generally within target.	*Corridor-wide travel times not assessed*	• 86% and 92% of segment travel times within 15% or one minute during AM peak and PM peak period respectively (as per requirements) • 85% to 92% of segment travel times within target for individual AM peak hours, and 31% to 85% of segments for individual PM peak hours. • Reference tachometric characterized lane-specific conditions that may not reflect the modeled average link behavior.	• Speed contour plots indicate good replication of location of front end of bottlenecks.

regional travel demand model instead of with Paramics. Paramics' dynamic information feedback feature was thus turned off, resulting in vehicles selecting their individual path upon entering the network and subsequently maintaining this path regardless of possible changes in traffic conditions. This is akin to assuming that motorists have no access to traffic condition information while driving, or to assume that drivers always ignore traffic information made available to them.

The calibration of the I-80 Paramics model resulted in a model that correctly steered vehicles to use the freeway to reach distant destinations and to stay on arterials to reach zones that are close by. However, the model remained sensitive to coding errors related to the calculation of travel times and travel costs. In this case, the presence of residual errors may explain some of the difficulties that were encountered in calibrating the route selection algorithms. For instance, the calculation of travel costs could have been affected by intersections with incorrect signal timings or barred turns. The difficulty of modeling the exact process by which travelers select a given path, and particularly the myriad of factors that may be considered when organizing travel plans, may have further contributed to the calibration difficulties.

For the I-405/SR-22 corridor, the default link cost model in Paramics was also set to equally weigh travel time and travel distance. However, no rationale was provided for this choice. Such an equal weighting is often encountered practice. In this case, however, cost perturbations were disabled, resulting in the assumption that drivers always have precise knowledge of travel costs. This may be realistic for networks primarily carrying commuters, as individuals tend to select their route based on prior experiences. The dynamic feedback option was also turned off, further resulting in vehicles selecting their path solely based on traffic conditions at the time they enter the network. In this case, a visual model review revealed no apparent major errors with the path selected by individual vehicles. This is in part helped by the fact that there are relatively limited alternate routing opportunities within the modeled network.

For the I-805 corridor, the calibration resulted in the selection of a stochastic shortest path algorithm instead of a probabilistic route choice algorithm. No other specific information is available regarding the calibration of route selection elements within the developed TransModeler model.

Link Travel Times / Speeds

The calibration of travel times, or speeds, appears to have been a more difficult task than for other parameters since all the reviewed models exhibit some link travel times that do not meet the calibration target within a given time period. These differences were not necessarily the result of improperly calibrated models, but rather the consequence of using driver behavioral models that attempt to model complex decision environments and real-world driver behavior using only a few parameters and equations. With this consideration, travel time differences over short segments can be considered acceptable if bottlenecks and overall travel times along the corridor are satisfactorily replicated.

Various factors exogenous to the simulation models may have also affected the modeling efforts, such as data quality and inherent variations in congestion levels. For most corridors, travel time data were collected from a relatively limited number of tachometric runs covering only between one and three days. It is therefore possible that the captured travel times do not exactly match the true average traffic behavior along of each corridor, particularly if significant differences exist in behavior from one lane to the next, or from one day to the next. Discrepancies between data collected or estimated from different sources may also explain some of the variations.

Bottlenecks

A strong emphasis was placed by all modeling teams on adequately replicating the location and extent of bottlenecks. This was expected given that bottlenecks are indicators of operational problems. All the modeling teams assessed the ability of the developed simulation models to replicate observed bottlenecks by visually comparing speed profiles developed from simulation outputs against similar profiles developed from field data. Assessments were made by comparing linear speed or travel time profiles, as shown in Figure 50, the locations of congestion hotspot against reference bottlenecks, as shown in Figure 51, or speed contour plots placed side-by-side, as illustrated in Figure 52.

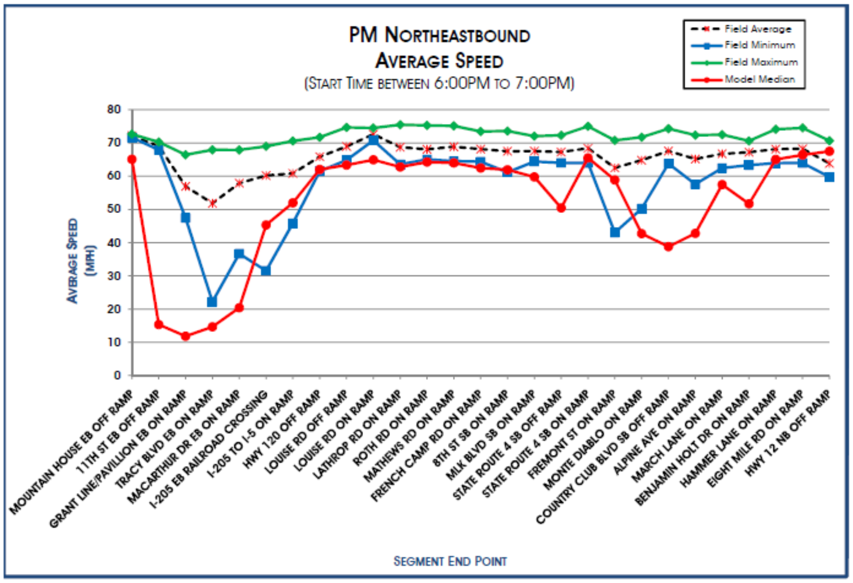


Figure 50 – Example of Linear Speed Profile Assessment

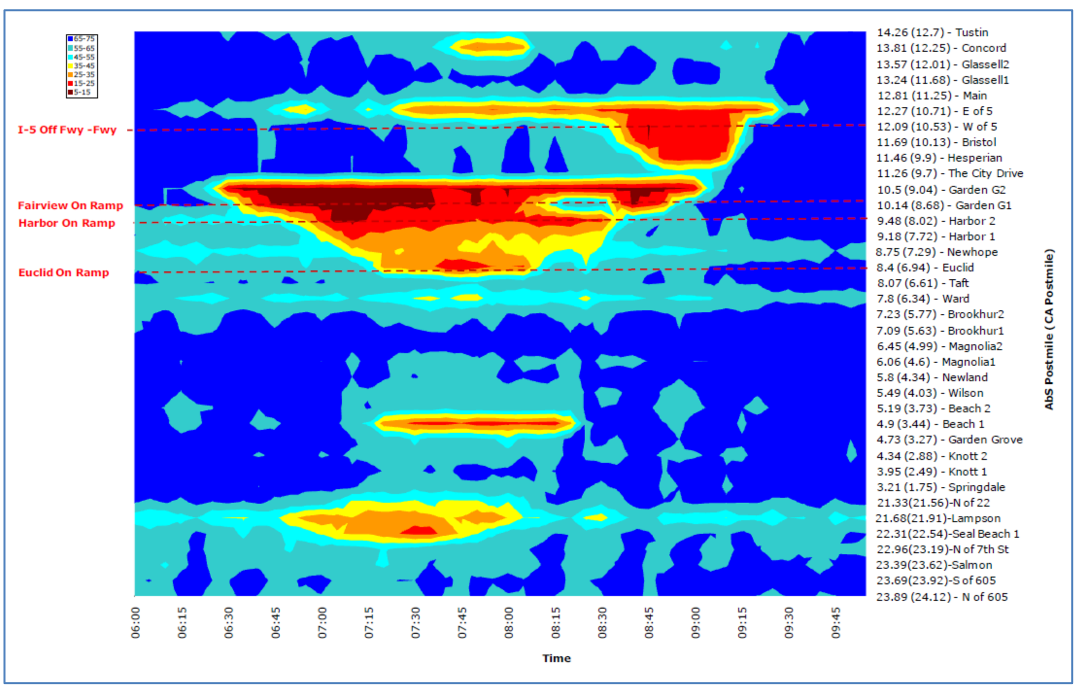


Figure 51 – Example of Bottleneck Location Analysis Using Speed Contours

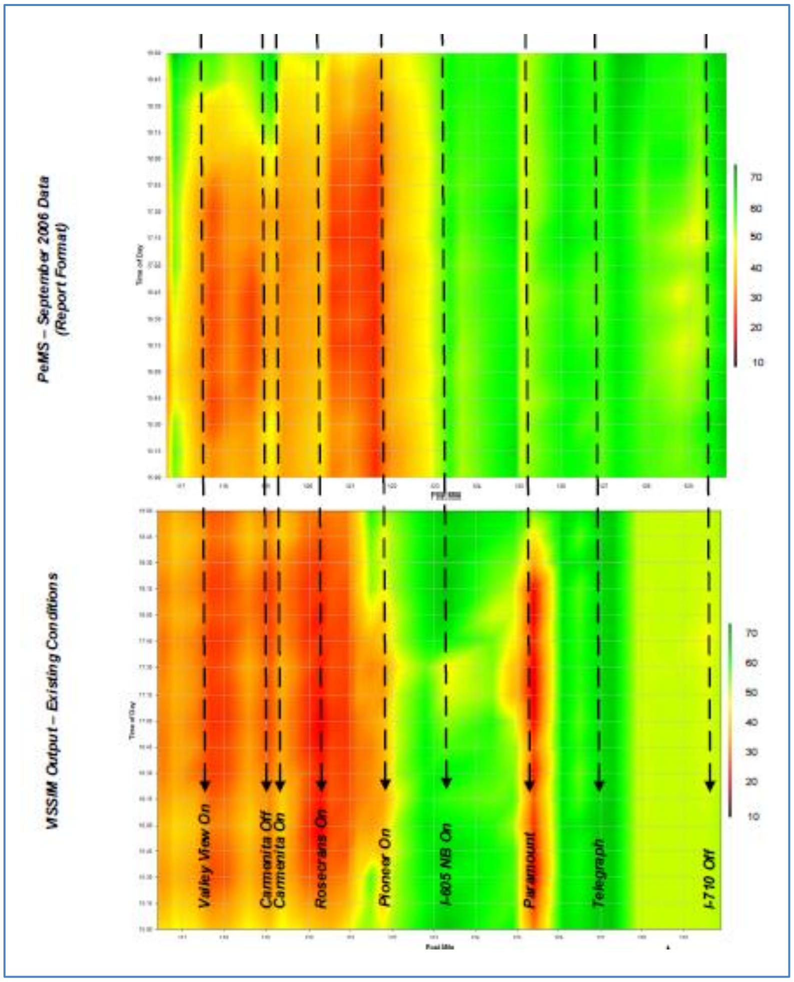


Figure 52 – Example of Comparative Analysis of Speed Contours

The last column of Table 29 further presents a general assessment of the ability of each model to replicate observed bottlenecks based on a review of information presented in calibration reports. In most cases, key major bottlenecks were replicated. This was expected as bottlenecks are often linked to changes in road geometry or busy freeway on-ramps. However, some differences can be observed with the start time, end time and physical extent of individual bottlenecks.

For a number of corridors, a notable difficulty was the variability of bottlenecks. While many bottlenecks tend to occur at the same location and time with a relatively well-defined reach, others can occur at varying locations and times, and have varying reach. To address this variability most modeling teams conducted calibrations against a fixed set of reference bottlenecks, typically those that were identified in the corridor's Comprehensive Performance Assessment report based on analyses of PeMS, HICOMP, probe vehicle and other field data. While this approach generally ensured the replication of key major bottlenecks, it did not eliminate the potential for differences. For instance, the data used for the modeling may have captured slightly different traffic demand levels or traffic patterns than the observations that were used to identify the reference bottlenecks. As an example, 2006 data were used for the analysis of bottlenecks on I-405, while 2008 data were used for the simulation modeling. Network improvements made after the Comprehensive Performance Assessment may have further altered traffic conditions on each corridor.

In addition to the variability of observed traffic conditions, modeling factors may be invoked as a source of differences, as simulation models will generally not perfectly replicate observed driver behavior. Simulation models will often start to exhibit the limitations of their driver behavioral models when simulating heavily congested conditions. This is partly due to the fact that drivers often act differently in severely congested and free-flow traffic conditions.

Model Stability

Model stability is a dimension that must not be overlooked. Due to their stochastic nature, variations in traffic performance will occur from one simulation run to the next, much alike what happens in reality from one day to the next, if the random number seed is changed. In some cases, this stochastic aspect can result in excessive variations if some of the underlying model parameters are not adequately calibrated. This is particularly true when simulating congested networks, as improper car-following or lane-changing decisions can increase behavioral frictions and caused unexpected congestion.

Evidence of stability tests were only provided in reports for the I-405 and SR-22 models. In both cases, the number of vehicles being simulated was compiled for each successive 5-minute interval and compared across 10 simulation runs using different random number seeds. The result of one such test is shown in Figure 53. These comparisons were performed to ensure that no excessive differences existed between individual simulation runs and that general traffic flow patterns were adequately reproduced across runs.

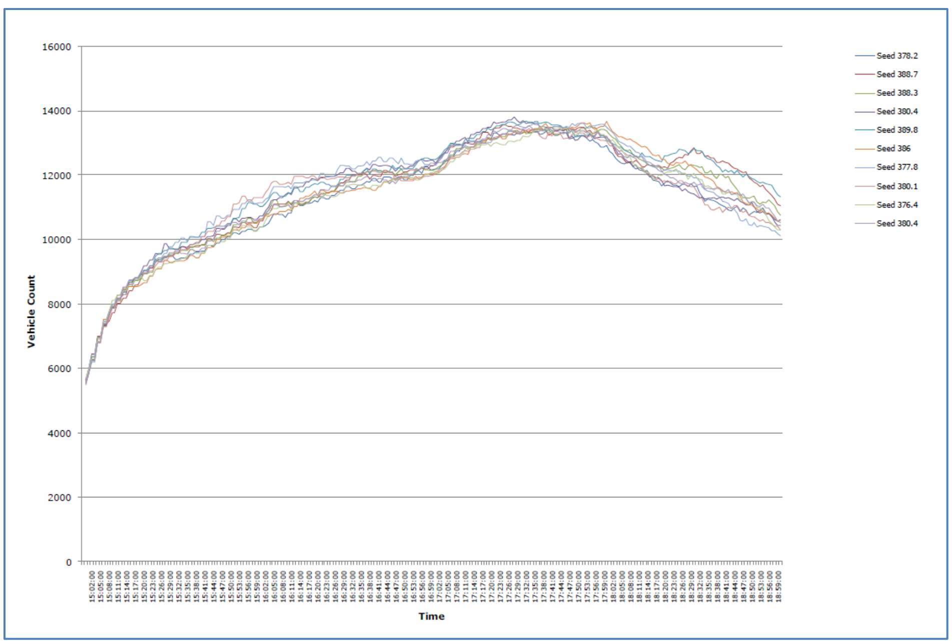


Figure 53 – Stability Test Example

5.9. PEER REVIEW AND APPROVAL PROCESS

In 2008, Caltrans developed a process for reviewing simulation models involving evaluations by independent sub-consultants. The reviewers were to evaluate whether each proposed simulation model would allow the CSMP team to adequately reflect the goals and objectives of each corridor study.

Model components and relevant tools were to be available for review, including customized plug-ins, spreadsheets, post-processing tools and external software files.

To accommodate overall project deadlines, each peer review was expected to be completed within a two-week period, which is a relatively short time. Because of time constraints, the review would focus on a high-level assessment and reasonableness check of the modeling approach and results. It was not intended to involve a comprehensive and detailed review of the model coding, nor was it required that each reviewer conducts separate model runs. However, should problems be identified, a more detailed examination of model details or new model runs could have been required to isolate the issue and develop the necessary corrective action.

The peer review was to be conducted at each of the following stages of the model development process:

Phase 1: Evaluation of model developing existing conditions;
Phase 2: Evaluation of models developing future-year base/no-build scenarios; and
Phase 3: Evaluation of models developing future-year scenarios.

A separate review was to be completed for each scenario submitted, including separate evaluations for scenarios considering the AM and PM simulation periods. In the case that a scenario Y relies on the results from a scenario X, if was further required that the model for the scenario X be reviewed prior to the development of model for the scenario Y.

At each stage, the review was expected to consist of three steps:

- **Step 1: Schedule Development** – The objectives of this step were to agree on a schedule for delivery and review of the applicable model(s) and to provide the independent consultant with all the information required to set up the test environment that will be needed later.
- **Step 2: Model Review** – Review of application simulation models. As noted above, the expectation was that a high-level assessment would be performed, and not necessarily a detailed review of model coding. Key review elements were to be a visual inspection of the model and a review of model animations to ensure that there were no unreasonable instances of vehicles demonstrating unusual behavior, such as vehicles being stuck, queue developing in the absence of downstream congestion, etc.
- **Step 3: Comment Meeting** – After completion of the peer review, a meeting was to be held to discuss the findings and any corrective measures that should be taken.

Table 30 summarizes key elements that were to be considered at each step of the review. Due to a variety of circumstances, the proposed process was not applied equally to all CSMP corridors. Below is a summary of how various Caltrans Districts validated their respective simulation models:

- District 4 used their own checklists to review the I-80 West and US-101 models. Unfortunately, there is no documentation detailing the process that was followed.
- District 7 staff had very little in-house skills to review the VISSIM simulation models that were being developed for the I-5 corridor. While consultant peer reviews were conducted, the District staff often only reviewed the report submitted. Ultimately, the decisions on the validity of the models were made by staff at Caltrans Headquarters.
- District 10 followed their own guidelines for the modeling of the I-205 corridor. Part of this decision was based on the fact that the District staff elected to model the corridor with CORSIM,

Table 30 – Peer Review Items

Model Aspect	Phase 1 – Base Year Model	Phase 2 – Future Year Base Model	Phase 3 – Future Year Scenarios
Focus of review	• Basic model setup and calibration to observed conditions	• Adjustments or modifications made to the existing conditions model, including assumed network improvements and demand forecasts.	• Coding of proposed improvements or strategies, associated changes to demand, and consistency of the results with related models.
Core model parameters / general consideration	• Assess if software is being used as intended. • Check if there is adequate documentation. • Check core simulation parameter settings and if adjustments made are reasonable.	• Check core simulation parameter settings • Check if core parameters are consistent with those used in the models representing existing conditions.	• Check core simulation parameter settings. • Check if core parameters are consistent with those used in the No Build Year models.
Network coding	• Review whether appropriate software features are used to represent network characteristics. • Check whether all segments are included in the model and with appropriate fidelity. • Check that geometric network elements have been coded properly. • If applicable, check the coding of traffic analysis zones to ensure that traffic can be loaded properly to the network and that the zone adequately represents the local street network area. • Check appropriateness of network representation across all models being developed.	• Check whether the future-year model is constructed based on the base-year model with planned/programmed projects properly added.	• Check whether the test scenarios are adequately defined and the comparisons well established. • Check if the model is adequately sensitive to the test strategy.
Traffic control elements	• Check the operational representation of the network for errors. • Check system management elements (such as ramp metering, transit signal priority, corridor-wide signal/metering coordination, etc.) to determine whether they are properly modeled (or an adequate explanation is provided of why they cannot be modeled). The reviewers might suggest alternative ways to model or confirm the limitations of the simulation software. • Review associated plug-in input parameters, if a customized plug-in is used.	• Check reasonableness of future-year signal timing plans. Check system management elements (ramp metering, transit signal priority, corridor-wide signal/metering coordination, etc.) to determine if they are properly modeled or if an adequate explanation is provided regarding why they cannot be modeled). • Review associated plug-in input parameters, if a customized plug-in is used.	• Review the source code and associated parameters, if a customized plug-in is used.

Table 30 – Peer Review Items (cont'd)

Model Aspect	Phase 1 – Base Year Model	Phase 2 – Future Year Base Model	Phase 3 – Future Year Scenarios
Demand representation	• Check entry demand values and profiles. • If applicable, check reasonableness of the methodology being used to estimate demand inputs for simulation (including but not limited to integration with travel demand models, zonal configuration, and temporal distribution of demands). If applicable, this should include a check of the methodology used to develop the ODME for simulation. • If applicable, check reasonableness of zone structure. This relates to the placement of the zones representing the locations where traffic enters or leaves the network. Observations related to sectors and zone connectors should be included in this section. • Check if entry demands are able to load onto the network during the duration of the simulation. Excessive un-released vehicles may cloud system-wide MOE scenario comparisons. • Check if excessive removal of struck vehicles has been improperly used. • If VISSIM is being used, check the coding of the Routing to ensure that all paths from possible origins and destinations are accounted for. • Check the vehicle type assumptions being used (vehicle classification, vehicle occupancy, vehicle performance).	• Check the steps taken to develop the future year demand inputs, in particular that quantification of the growth scenario and estimation of the future year O-D Matrix (if applicable) is reasonable. • Review the responsiveness of model system to potential demand shifts in terms of mode choices, route choices, and peak spreading that may be associated with future growth and assumed network improvements. • Check the future-year demand to determine whether it is properly forecasted and comparable to the base-year demand in assumptions and format. • Check that required modifications to the traffic analysis zones are made to reflect the future base year. • Check if entry demands are able to load onto the network during the duration of the simulation. Excessive un-released vehicles may cloud system-wide MOE scenario comparisons. • Check if excessive removal of struck vehicles has been improperly used.	• Review the responsiveness of model systems to potential demand shifts in terms of mode choices, route choices, and peak spreading. • Check whether demand inputs for the Future Base Year Scenario are suitable for simulating the proposed alternative scenario(s) and whether adjustments are necessary. • Check whether entry demands are able to load onto the network during a simulation run. • Check if excessive removal of struck vehicles has been improperly used. • Check traffic assignment principles across all models: ○ For minor improvement, check that there is no major change in route choices. ○ For major improvements: check that route choices changes are based on equilibrium flows and that appropriate stopping criteria for convergence are used.
Data collection and Reduction	• Check the data collection plan, methodologies and assumptions used to identify gaps in data. • Check that the proposed data collection locations to fill in the identified gaps. • Check that bottleneck locations have been properly identified, and that appropriate data has been collected to verify their location, causality, length and duration. • Check the steps taken to reduce the data for input into the simulation model or Origin Destination Matrix Estimation for reasonableness. • Check reasonableness of the methodology being used to estimate demand inputs for simulation. • Check that the travel time data collected and the methodologies and assumptions that were used for the collection and reduction of travel time data are reasonable.		

Table 30 – Peer Review Items (cont'd)

Model Aspect	Phase 1 – Base Year Model	Phase 2 – Future Year Base Model	Phase 3 – Future Year Scenarios
Output reporting and consistency with related models	• Review whether measures of effectiveness (MOEs) are well defined and consistent across scenarios. • Check that the segmentation for reporting output and calibration statistics is reasonable, with a particular attention on its ability to capture bottlenecks effects. • Review the reported MOES for each directional subsection (freeway mainline, on-ramps, off-ramps, and parallel arterial). This should include volume, travel time, delay, speed, VHT, VMT, and Q-ratio in an hourly format. Hourly statistics should be based on 15-minute results. • Review the process for producing MOEs. If external software is used, its output is to be reviewed to verify appropriateness of data processing and consistency with the MOEs generated by the simulation software.	• Review whether the generation and reporting of MOEs are consistent across scenarios. • Check that the model segmentation for reporting output is reasonable. • Check that results appear reasonable and are consistent with related models given the forecasted growth and assumed improvements.	• Review whether the generation and reporting of MOEs are consistent across scenarios. • Check that the model segmentation for reporting output is reasonable. • Check whether the differences among scenario models are well documented and consistent with what implemented in the model. Each scenario model shall be verified that there is no unreasonable change.
Calibration approach and results	• Review the calibration approach and data being used • Check that that the model(s) have been run the appropriate amount of times, with seed tables and warm up periods. • Check that any changes to defaults pertaining to driver behavior and car following parameters are warranted and supported by data and field observations • Review calibration results to determine whether they are properly generated and are within the FHWA's calibration criteria set for the specific corridor. • Review the cause and location of each bottleneck to determine whether they are consistent with what has been identified in the Performance Assessment Report. • Review the temporal and spatial extents of each bottleneck to determine whether they are acceptably calibrated. • Identify problems from the animation and provide advice for appropriate changes to address the problems.		

which is an older simulation model that does not offer all the capabilities provided by other microscopic tools.

- District 11 sat with Cambridge Systematics staff to review the modeling of the I-805 corridor in TransModeler. This approach was adopted because the District did not have staff with the capability to run TransModeler and conduct independent reviews on their own. This situation can be partly explained by the relatively recent availability of the simulation model.
- District 12 conducted some peer reviews and submitted peer review checklists for the I-405/SR-22 corridor. However, due to time constraints, the peer review team was told by the project managers not to conduct detailed reviews of the scenario models.

5.10. IMPROVEMENT PROJECTS CONSIDERED

Table 31 presents the types of improvement projects that were evaluated for the six reviewed corridors. The projects typically fall within one of the three following categories:

- **Capital investments** – Freeway widening, construction of auxiliary lanes, modifications to existing interchanges, construction of new interchanges, addition of HOV lanes, addition of HOV connectors between freeways, improvements to freeway collectors distributors, etc.
- **Operational strategies** – Installation of new traffic signals, improved traffic signal coordination, lane restriping, addition of HOV bypass lanes on existing freeway ramps, installation of new ramp meters, implementation of adaptive ramp metering, implementation of transit lanes, improvements to Bus Rapid Transit (BRT) services, etc.
- **System management strategies** – Strategies to reduce responses to incidents, management of reversible traffic lanes, evaluation of pricing programs for goods movement/freight operations by medium-duty commercial vehicles, etc.

Table 31 – Improvement Strategies Considered

Corridor	Freeway widening	Lane restriping	Auxiliary Lanes	Managed Lanes	Variable Speed Limits	Interchange Improvements	Ramp Widening/changes	New Ramp Meters	Change to Ramp Metering Layout	Adaptive Ramp Metering	Enhanced Incident Management	Addition/Extension of HOV Lanes	Ramp Meter HOV Lanes	HOV Direct Access Ramp	Arterial Widening/Extension	New Traffic Signals	Traffic Signal Coordination	Bus Rapid Transit Operational	Dedicated Transit Lanes	Value Pricing Program
I-80 West			●	●	●	●	●			●					●					
US-101	●		●				●	●				●								
I-5 North	●	●				●	●			●	●	●		●						
I-5 South	●	●	●			●	●		●	●	●									
I-205 / I-5	●		●			●	●	●				●	●	●	●					
I-805			●	●		●		●				●	●	●		●	●	●	●	●
I-405/SR-22	●		●			●	●	●		●	●	●		●						

Many of the improvement projects were identified or developed from projects listed in Regional Transportation Improvement Programs (RTIP), Regional Transportation Plans (RTPs), projects tied to specific ballot measures, and various special studies. Some corridors also included projects that were submitted for consideration by the evaluation team.

Most of the improvement strategies focused on the freeway mainline, ramps, and interchanges. Improvements to parallel arterials were also considered in a few cases. For instance, evaluations for the I-205/I-5 corridor included projects that sought to widen three arterials (Lathrop Road, Louise Avenue, and Airport Way) and extend another one (Sperry Road). The I-805 corridor further included a project to improve signal coordination along Broadway Street in Chula Vista and another one to improve coordination on H Street, from I-805 to I-5. Projects that did not affect mobility or productivity were typically not considered, since most simulation models could not evaluate such projects.

Evaluations typically did not look at potential demand management strategies, such as the introduction of rideshare programs, programs to entice time shifts or mode shifts, etc., due to limitations associated with the simulation tools being used. Current models cannot typically simulate the impacts of changes in network geometry or operational conditions on the number of trips generated within a corridor. While models such as Paramics, VISSIM and TransModeler can simulate dynamic route changes, these changes are typically derived from an underlying static O-D flow matrix. To evaluate traffic demand effects, an iterative process involving both a traffic simulation and a travel demand forecasting model must typically be used.

5.11. SCENARIO DEVELOPMENT

The number of improvement projects considered did not allow model developers to assess the impacts of all potential combinations of improvements. For instance, evaluating every possible grouping associated with 10 projects would result in 1023 possible combinations. In addition, each combination would normally need to be simulated multiple times to adequately consider the stochastic effects associated with the simulation tool being used. Such an extensive simulation effort was beyond the resource allocated to most, if not all, CSMP corridors. Because of time and budgetary constraints, evaluations were thus restricted to about a dozen scenarios per corridor, with each scenario including one or more potential improvements.

5.11.1. CORRIDOR IMPROVEMENT SCENARIOS

In most cases, scenarios were developed by grouping projects based on their expected delivery. A frequently considered grouping included the following categories:

- Projects already funded and programmed;
- Projects to be delivered within five years of the base year (typically around 2014 or 2015); and
- Projects to be completed between 2020 and 2030.

The assignment of projects to specific evaluation horizons was then generally performed along the following guidelines:

- Projects already funded and programmed were included in the base year scenario, since they were likely to be implemented regardless of the results of the CSMP operational evaluations.

- Projects to be delivered within five years were included either in the base year model or evaluated at the 2014 or 2015 horizon. The former approach was followed for the I-805, I-5 and I-405/SR-22 corridors, while the later was used for the I-80, US-101 and I-205/I-5 corridors. For the I-805 corridor it was more specifically argued that projects to be delivered before 2014 could be evaluated with the 2006 base year simulation model since the economic recession had caused significant reductions in traffic volumes along the corridor. It was notably observed that the 2009 traffic volumes along the corridor were lower than the 2006 observed volumes, thus leading to the argument was that the available 2006 base year model could adequately reflect conditions that were then expected to prevail in 2010 or 2011.
- Projects expected to be delivered beyond 2014 or 2015 were considered as medium or long-term projects and evaluated over 2020, 2024 or 2030 horizon. The I-80 corridor is the only one for which no long-term evaluations were made, as it was assessed that the high levels of congestion expected to exist along the corridor then would not allow realistic evaluations to be conducted with the Paramics microscopic simulator.

Following the assignation of projects to a specific horizon, improvements were bundled into groups that could be evaluated together. As indicated earlier, this was done to save time and resources. For instance, project bundles could include various auxiliary lane implementation projects or projects that could be implemented at the same time, such as improving an interchange at the same time as building HOV lanes on the freeway mainline. High-profile or large-scale projects were generally kept separate to facilitate the identification of impacts specifically associated with them.

Figure 54 to Figure 59 illustrate the scenarios that were developed for each corridor. The scenarios were typically developed using an additive strategy. Starting from the base year model representing current conditions, a first scenario was developed by implementing a first bundle of improvements. A second scenario was then developed by adding a new bundle to the preceding scenario. The following details the specific strategies that were followed within each corridor to determine the sequence in which various bundles of improvements should be evaluated:

- **I-80 West** – The evaluations considered two major groups of projects over the 2015 horizon: core CSMP improvement projects and potential intermediate-term projects. Core projects included the installation of ramp meters, use of variable speed limits to promote speed harmonization and provide end-of-queue warning, and the introduction of a managed lane system. This small number of projects allowed considering every possible combination. Ramp metering improvements were assumed to be implemented first, followed by the variable speed limits, and the managed lanes. Since intermediate improvements were assumed to be delivered further in time, they were implemented in scenarios adding them to the core improvements, with the more costly interchange improvements added last.
- **US-101 San Mateo** – A single scenario including all projects that could be implemented by 2015 was developed for the short-term evaluation. For the 2020 horizon, two scenarios were developed based on the potential offered by each project to reduce congestion. Low level improvements that would allow congestion to remain within the current 4-hour AM peak and 5-hour PM peak period were grouped in the first scenario. Projects that could eliminate all existing recurring congestion, under the assumption that the considered improvements would not attract more traffic demand, were then grouped in a second scenario. This approach implied a certain a priori knowledge of the potential impacts of each strategy considered.

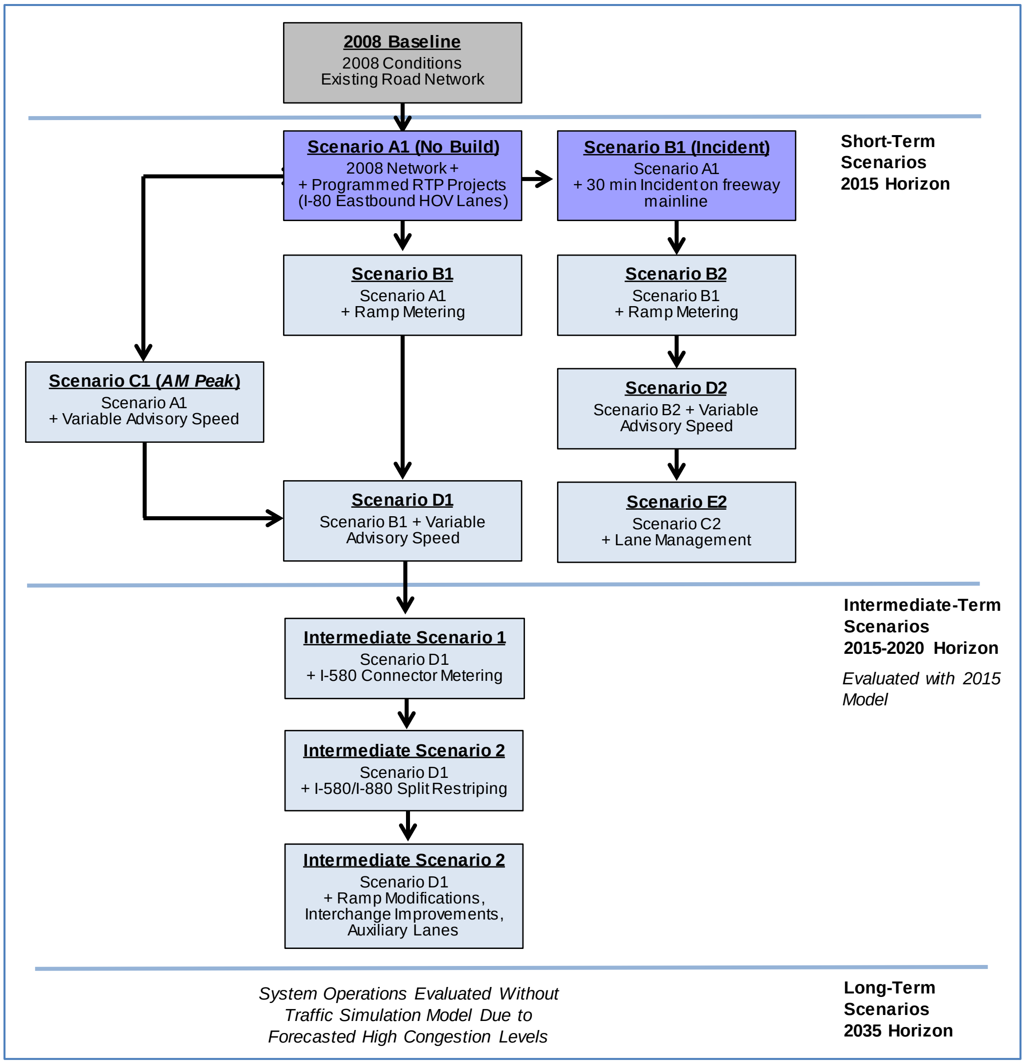


Figure 54 – Evaluation Scenarios for I-80 West Corridor

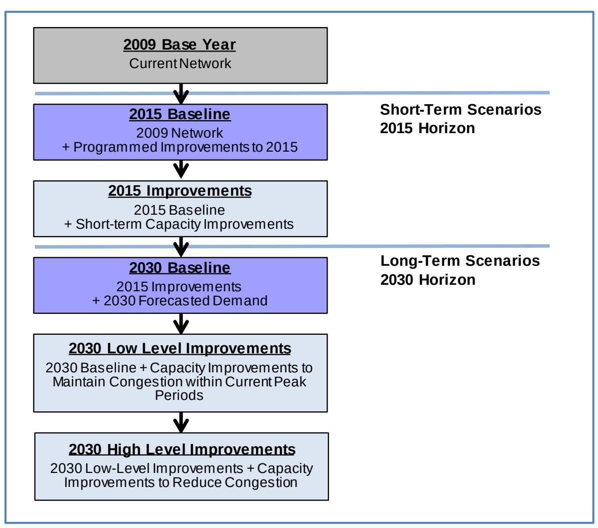


Figure 55 – Evaluation Scenarios for US-101 South Corridor

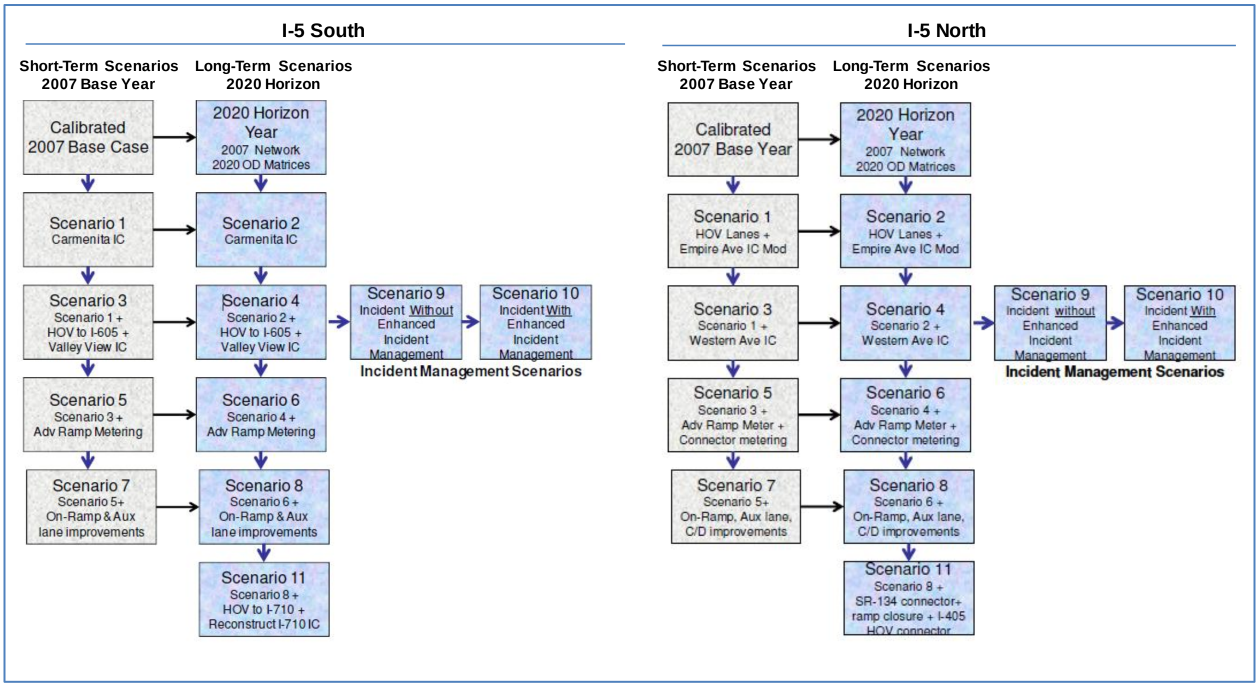


Figure 56 – Evaluation for I-5 North and I-5 South Corridors

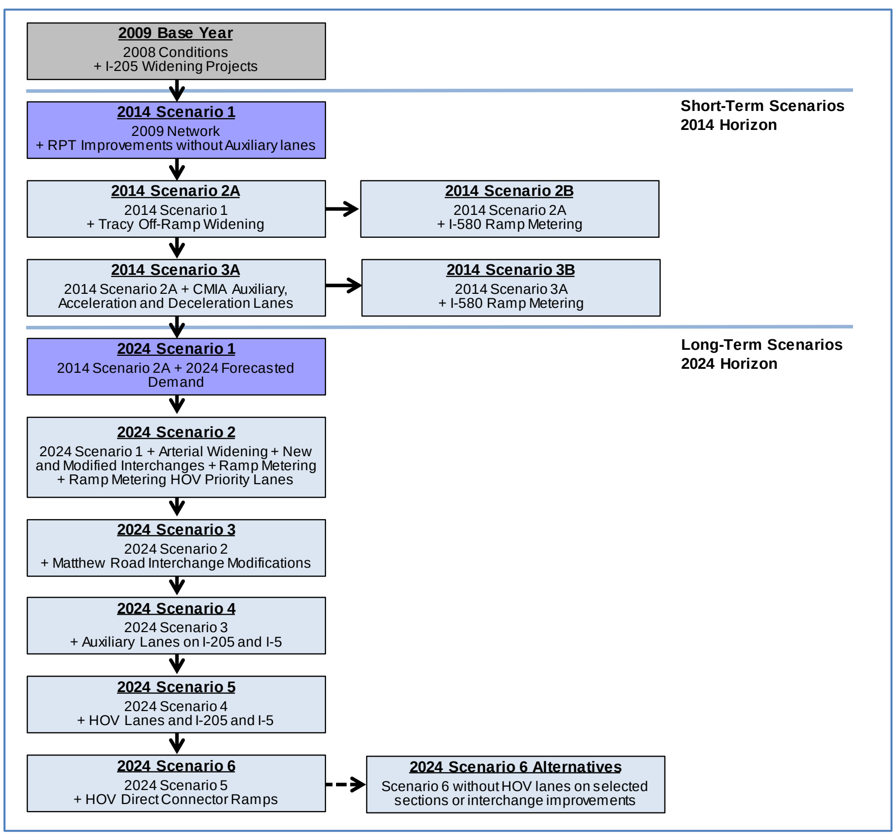


Figure 57 – Evaluation Scenarios for I-205/I-5 Corridor

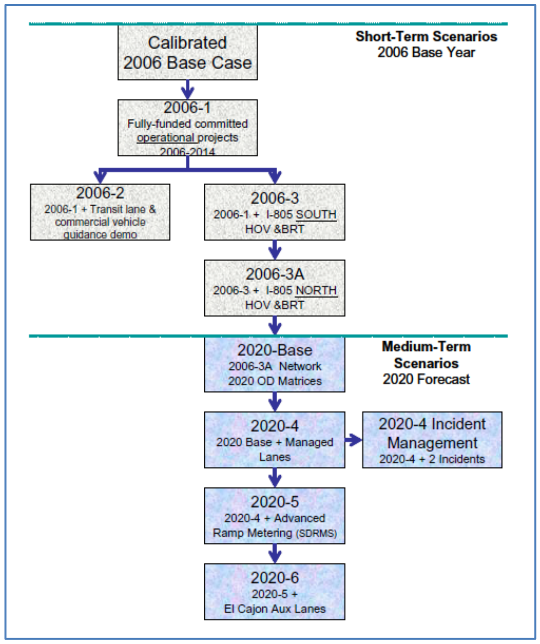


Figure 58 – Evaluation Scenarios for I-805 Corridor

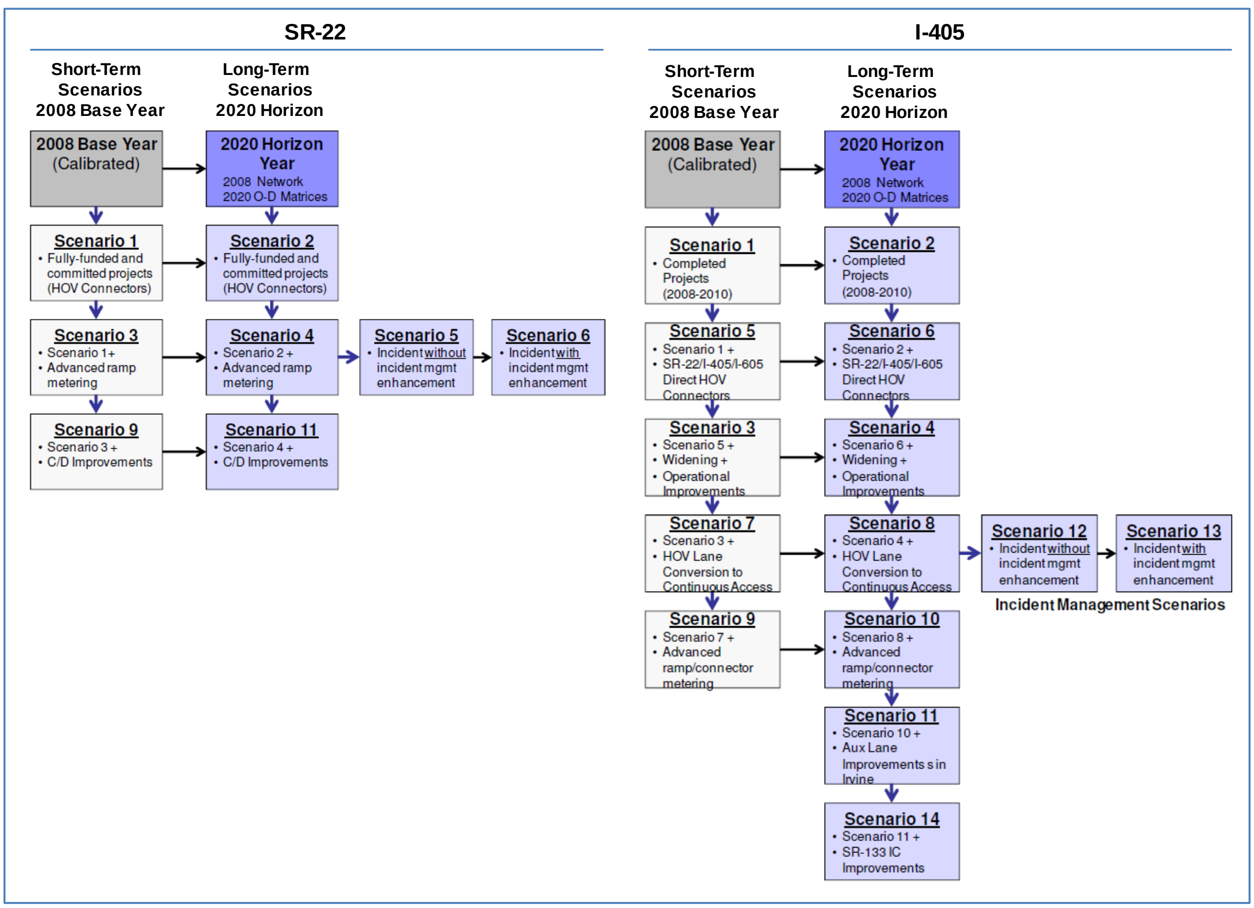


Figure 59 – Evaluation Scenarios for I-405/SR-22 Corridor

- **I-5 Los Angeles** – Twelve scenarios were developed to analyze potential corridor operations along the I-5 North and South corridors. Projects already programmed or under consideration were typically added first, before suggested improvements. Improvements considered for this corridor essentially consisted of a variety of geometric improvements and improvements to ramp meters. While this was not always the case, geometric improvements were generally added first, before the ramp metering improvements.
- **I-205/I-5 San Joaquin** – Improvements scenarios for 2014 primarily sought to address congestion simulated to develop during both the AM and PM peak periods due to insufficient off-ramp capacity at the I-205/I-580 merge. A scenario widening the off-ramp at the Tracy Boulevard interchange is first considered. Since this scenario did not eliminate all queuing, various additional improvements were then considered in a separate scenario. In both cases, the introduction of ramp metering at the I-205/I-580 was evaluated separately to highlight the impacts associated with this project. For the 2024 horizons, scenarios implementing interchange improvements, freeway widening and arterial widening projects were developed first, followed by scenarios adding HOV lanes and HOV direct connectors. Additional preliminary scenario testing was further performed by incrementally removing segments of the proposed southern I-5 HOV lane widening and some of the proposed I-5 auxiliary lanes to determine if any of these improvements could be removed without degrading traffic operations.
- **I-805/I-5 San Diego** – For the 2006 base year, scenarios implementing fully-funded, committed operational projects were grouped into a first scenario. Two scenarios implementing HOV lanes in both directions were then developed based on the first scenario (Scenarios 3 and 3A). A scenarios implementing transit lanes and commercial vehicle guidance was also developed based on the first scenario as a separate alternative. The 2020 horizon scenarios further build upon the 2006 scenarios by implementing HOV lanes. New scenarios added in turn a managed lane system, advanced ramp metering, and auxiliary lanes.
- **SR-22 Orange County** – Parallel improvement tracks were considered for the 2008 base year and 2020 horizon. In both cases, a scenario implementing fully-funded, committed operational projects was first developed (scenarios 1 and 2). Scenario adding advanced ramp metering was then developed based upon the previous scenarios (scenarios 3 and 4), followed by scenarios adding various collector-distributor improvements (scenarios 9 and 11).
- **I-405 Orange County** – Similar to the SR-22 corridor, parallel improvement tracks were considered for the 2008 base year and 2020 horizon. In both cases, scenarios implementing fully-funded, committed operational projects were first developed (Scenarios 1-2). Successive scenarios then added direct HOV connectors at the SR-22/I-405/I-605 interchange (Scenarios 5-6), various widening and improvement projects (Scenarios 3-4), an HOV lane conversion to continuous access (Scenarios 7-8), an advanced ramp metering system (Scenarios 9-10), localized auxiliary lanes (Scenario 11, 2020 only) and improvements to the SR-133 interchange (Scenario 13, 2020 only). Here, the non-consecutive numbering of scenarios suggests that a different scenario development order than the one that was actually used was initially planned.

5.11.2. INCIDENT MANAGEMENT IMPROVEMENT SCENARIOS

To evaluate the benefits provided by enhanced incident management procedures, scenarios involving vehicles blocking freeway lanes were developed for a number of corridors:

- **I-80 West** – A baseline scenario implementing an incident along I-80 (Scenario B1) was developed based on the existing network. Evaluations then considered the ability of using ramp meters (Scenario B2), a variable speed advisory system (Scenario D2) and a managed lane system (Scenario E2) to help management traffic around the incident.
- **I-5 Los Angeles** – For each peak period, a baseline scenario assumed that the leftmost freeway lane would be blocked by a vehicle for 35 or 40 minutes. This scenario was developed from the scenario implementing HOV lanes and critical interchange improvements. A second scenario assuming that the incident could be cleared in 25 to 30 minutes was then developed to evaluate the impacts of enhanced incident management protocols.
- **I-805/I-5 San Diego** – A baseline scenario reflecting current incident clearance practice was developed using the 2020 demand scenario and a network featuring a managed lane system. The managed lane system was included as it is viewed as a key component for enhanced incident management. The baseline scenario assumed that an incident would block two freeway lanes in the peak travel direction of travel for 45 minutes, causing traffic to bypass the incident at 30 mph. It also assumed that the managed lanes could be opened to all traffic 15 minutes after the start of the incident. The second scenario assumed that one of the two blocked lanes could be reopened 30 minutes after the incident occurred, and that the managed lanes would be opened to all traffic within 10 minutes of the incident.
- **I-405/SR-22/I-605 Orange County** – Baseline incident scenarios were developed for both the AM and PM periods for the I-405 and SR-22 corridors based on scenarios implementing some of the improvements considered. For the I-405 corridor, the baseline scenario (Scenario 12) assumed that a vehicle would block the leftmost freeway lane in the peak direction of travel for 35 minutes. For the SR-22 corridor, the blockage is assumed to last 50 minutes in the AM peak period and 80 minutes in the PM peak period (Scenario 5). For each corridor and time period, a follow-up scenario assuming an ability to reduce incident clearing by 10 to 14 minutes, based on assessments from Caltrans, was then developed.

5.12. PLUG-IN REQUIREMENTS

While state-of-the-art simulation models generally allow commonly encountered transportation systems elements to be modeled using built-in features, many of the CSMP improvement projects required the modeling of traffic control or management systems not commonly available in the libraries of existing tools, such as dynamic ramp metering algorithms.

To help address the above limitations, many simulation tools offer the ability to introduce new functionalities through the utilization of plug-in modules. Table 32 lists the plug-ins modules that were used to expand the capabilities of the simulation tools that were used for each corridor. For each plug-in, the table indicates its function and whether it was available prior to the start of the modeling or was specifically developed for the CSMP operational evaluations. The most common plug-ins were modules allowing Paramics, VISSIM and TransModeler to replicate existing or proposed ramp metering system operations, specifically the ALINEA, TOS, SATMS, and SDRMS algorithms. No plug-ins were used for the US-101 model since FREQ 12 did not offer the ability to add externally-developed modules. The modelers for the I-805/I-5 corridor also sought to utilize plug-ins to simulate ramp metering strategies along the corridor. However, the intended plug-ins were not developed in time for use in the CSMP operational evaluations. The desired ramp metering operations were thus approximated by adjusting the pre-timed ramp metering parameters available within TransModeler.

Table 32 – Plug-ins Used with CSMP Simulation Models

Corridor	Simulation Model	Plug-in	Usage	Origin
I-80 West	Paramics	QP HOV Weaving/No Weaving	Models usage of HOV lanes by HOV vehicles.	Provided by simulation software developer.
		Lane Management	Model lane closures during incidents and driver responses to messages on Changeable Message Signs.	Developed by CLR Analytics specifically for the I-80 CSMP.
		Freeway MOEs	Collects travel times between sensors.	Originally developed by the University of California, Irvine. Upgraded to version 6.6.1 by CLR Analytics, with some modifications to plug-in outputs as part of the CSMP effort.
		Loop Aggregator	Gathers and aggregate detector data for every time step.	
		ALINEA Ramp Metering	Implements the ALINEA ramp metering algorithm.	
		TOS Ramp Metering Control	Implements the Traffic Operations System ramp metering algorithm used by Caltrans District 4.	
		SATMS Ramp Metering	Implements the ramp metering algorithms from the Semi-Actuated Traffic Metering System.	
		SDRMS Ramp Metering	Implements San Diego Ramp Metering System algorithms.	
US-101	FREQ 12	*No plug-in used*	n/a	n/a
I-5	VISSIM	SATMS Ramp Metering	Simulates the semi-actuated traffic metering control used within Caltrans District 12.	Initially developed by CLR Analytics outside CSMP modeling effort.
		ALINEA Ramp Metering	Implements the ALINEA ramp metering algorithm.	
I-205 / I-5	CORSIM	*No plug-in used*	n/a	n/a
I-805	TransModeler	SDRMS Ramp Control	Replicates the SDRMS ramp metering used in Caltrans District 11.	Initially developed for I-5 San Diego CSMP by CLR Analytics.
I-405 / SR-22 / I-605	Paramics	QP HOV Weaving	Models usage of HOV lanes with lane weaving option	Provided by simulation software developer.
		QP HOV No Weaving	Models usage of HOV lanes with without lane weaving	
		Freeway MOEs	Collects travel times between sensors. Collected data was used for journey time calibration.	Originally developed by the University of California, Irvine. Upgraded to version 6.6.1 by CLR Analytics, with some modifications to plug-in outputs as part of the CSMP effort.
		Loop Aggregator	Gather and aggregate detector data for every time step. Collected data was used for the speed calibration of the model.	
		ALINEA Ramp Metering	Models the ALINEA feedback local ramp metering algorithm.	
		SATMS Ramp Metering	Implements the ramp metering algorithms from the Semi-Actuated Traffic Metering System.	
		Vehicle Lane Control	Model the range of lanes and speeds that trucks are allowed to operate	
		Link Choice	Assign vehicles to downstream links based on pre-determined percentages. One application is to make HOV vehicles on the ramp to select HOV bypass lane when HOV and metered lanes for single-occupancy vehicles are modeled as separate links.	

5.13. MODEL APPLICATION

Table 33 summarizes the model application parameters for the six reviewed CSMP corridors. The subsections that follow provide more detailed comments on the information listed in the table.

Table 33 – Model Application Parameters

Corridor	Model Type	Model	Number of Replications	Warm-up Period	Warm-up Demand	Simulation Time Step
US-101	Macroscopic	FREQ 12	1	none	---	1 hour
I-80 West	Microscopic	Paramics	1	60 min	*n/a*	0.2 s
I-5	Microscopic	VISSIM	5	60 min	100% of first period demand	0.2 s
I-205 / I-5	Microscopic	CORSIM	9-11	*n/a*	*n/a*	1.0 s
I-805	Microscopic	TransModeler	12	30 min	90% of first period demand	0.5 s
I-405/SR-22	Microscopic	Paramics	10	60 min	75% of first period demand	0.5 s

5.13.1. NUMBER OF RUNS

Across the reviewed corridors, the number of simulation runs executed with different number seeds to assess average traffic conditions varied from 1 to 12. While some modeling teams executed as many runs as necessary to achieve a certain confidence level, others selected the number of runs based on prior modeling experience. For some corridors, the task order also directly stipulated an exact or minimum number of runs to execute.

As reported in Table 33, two corridors based their evaluations on a single simulation run. For the US-101 corridor, a single run was justifiable due to the macroscopic nature of the FREQ 12 model. However, the use of a single run for the I-80 corridor is questionable. Even if the model had been adequately calibrated, there is no guarantee that the single runs that were considered for the evaluation of each scenario truly replicated the average traffic conditions along the corridor. While the calibration process may have created a simulation setup that satisfactorily replicated observed traffic conditions, the modeling of corridor improvements has likely caused a change in the sequence in which random numbers are sampled, and thus, some changes in traffic behavior. It is therefore possible that the individual simulation runs that were produced for each evaluation scenario deviated noticeably from the average conditions used a reference.

Among the corridors, the I-205/I-5 is the only one for which the utilization of a statistical formula to determine the number of runs to execute is documented. This number of runs was based on a desire to achieve a statistically valid median travel time with a 5% tolerable error and a 95% confidence interval under the assumption that travel times are normally distributed. When considering the variability of end-to-end corridor travel times, a single simulation run was estimated to be required. However, 11 runs were required when considering the variability of travel times along I-205 eastbound freeway segments. The largest number of runs, 11, then was retained. While all evaluations should have been made on the basis of 11 runs, some evaluations were made against a median of only 9 runs, as some of the runs resulted in fatal errors and were apparently not replaced with new runs.

5.13.2. WARM-UP PERIOD

A warm-up period is used to load the network with representative traffic before starting the evaluation. The duration of the warm-up period and magnitude of the traffic demand to be simulated within the period typically depend on the network being simulated. A frequently recommended practice is to have a warm-up period long enough to allow the vehicles with the longest travel times to reach the end of the network, at least along major travel paths. A demand slightly less than the demand of the first period is often simulated, particularly if the warm-up period is at the beginning of the peak travel period. The key here is to set the demand at a level that would allow the queuing and travel conditions that would exist in the network at the beginning of the evaluation to be replicated.

5.13.3. SIMULATION TIME STEP

The time-step defines the interval between successive time increments within a simulation. While many early microscopic models were developed based on the use of a 1.0 s time step, many models now allow time steps as short as 0.1 s. Shorter time steps allow vehicles to assess more frequently their behavior. As a result, shorter time steps can increase lane changing and gap-acceptance opportunities, as well as lead to smoother overall behavior. Short time steps are often recommended for simulating congested networks or networks with complex interactions. However, they also increase computational load and simulation run time. Depending on the time available, a compromise may thus need to be made between desired simulation fidelity and execution time.

Across the reviewed corridors, the selected time step in evaluations using microscopic models varied between 0.2 and 0.5 s. This range appears to be adequate for the evaluations. The US-101 corridor is the only one using a longer time step, in this case 1 hour. This is explained by the macroscopic nature of the CORSIM model. Since this model simply processes flow rates, a 1-hour or 15-minute time step would not technically affect the simulation results. The utilization of a 1-hour time step was therefore imposed by the hourly nature of data that were used to model the traffic demand.

5.14. SCENARIO EVALUATION

This section reviews the criteria and parameters that were used to assess the impacts of proposed improvements on corridor performance. The topics reviewed include:

- Corridor segmentation;
- Post simulation data processing needs;
- Performance measures that were used for the initial corridor performance assessment;
- Performance measures that were used to assess the operational impacts of proposed improvements;
- Estimation of projected improvement costs; and
- Benefit/cost analysis approach.

5.14.1. CORRIDOR SEGMENTATION

Table 34 lists the various segmentations that were considered to evaluate corridor performance across the various corridors. As expected, network-wide performance measures were compiled for all corridors, as well as measures assessing travel conditions along major travel directions. Except for the

US-101 corridor, performance measures were further compiled by segment along the freeway mainline. This was done to account for the fact that not every vehicle may travel the entire corridor, as well as to better assess the impacts of proposed improvements on local congestion hotspots.

Table 34 – Segmentation of Performance Measures

Category	I-80 West	US-101	I-5 North	I-5 South	I-205 / I-5	I-805	I-405	SR-22
Corridor-wide performance								
Network-wide statistics	●	●[1]	●	●	●	●	●	●
Freeway Mainline Segmentation								
Directional analysis	●	●	●	●	●	●	●	●
Segmented by key interchanges	●	●			●			
Segmented by bottleneck areas			●	●		●	●	●
Number of defined segments, per direction	3	3	7 NB 7 SB[2]	6 NB 6 SB[2]	4	5 NB 5 SB[2]	8 NB 12 SB	6 EB 4 WB
Arterial Segmentation								
Directional analysis	●							
Segmented by key intersections	●							
Number of defined segments, per direction	3							
Analysis by Facility Type								
Freeway links	●		●	●		●	●	●
HOV Lanes			●	●			●	●
Managed Lanes						●		
Ramps	●		●	●		●	●	●
Arterial links	●		●	●		●	●	●
Intersections								

1. Only for evaluations of corridor performance between I-280/I-680 to Yerba Buena Road using VISSIM
2. Northbound and southbound segments do not necessarily have the same boundaries

Depending on the corridor, the segmentation was based on the location of key major interchanges or bottlenecks. In the first case, freeway-to-freeway connectors or interchanges with major regional highways were selected as key segmentation points. For the I-80 corridor, SR-4 and Central Avenue, near the I-80/I-580 split were the segmentation end points for both the freeway and San Pablo arterial, as shown in Figure 60. For the I-205/I-5 corridor, the segmentation end points were the I-205/I5, SR-120 and SR-4 interchanges. This approach resulted in 3 to 4 segments per travel direction. For the I-405/SR-22 corridor, key bottlenecks were used a segmentation end points based on the principles illustrated in Figure 61. This resulted in a different segmentation for each travel direction, with 4 to 12 sections per direction, as shown in Figure 62.

In addition to the geographical segmentation, the I-80, I-5, I-805 and I-405/SR-22 corridors include a compilation of performance measures by facility type. This allowed evaluating the performance of specific elements, such as general purpose freeway lanes, HOV lanes, ramps, and arterials.

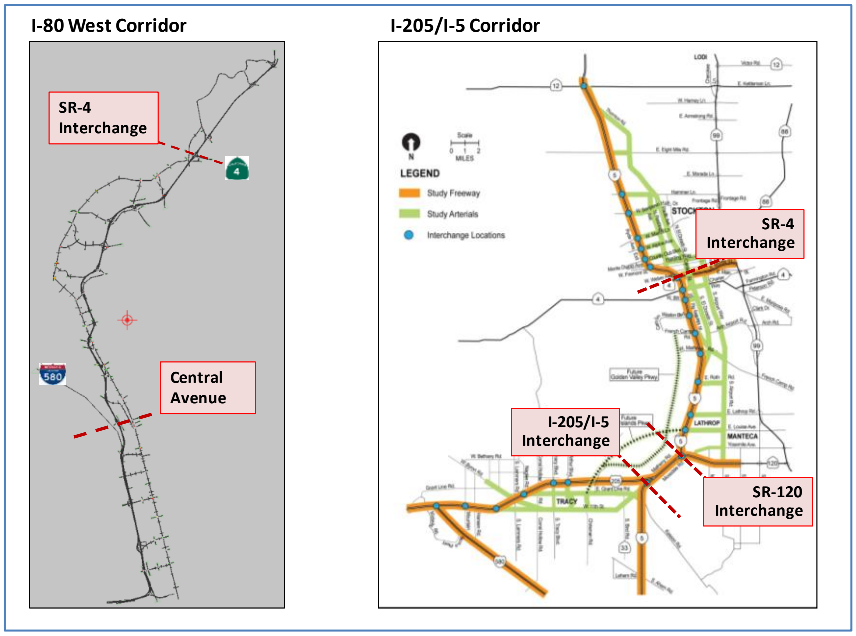


Figure 60 – Interchange-Based Segmentation Examples: I-80 West and I-204/I-5 Corridors

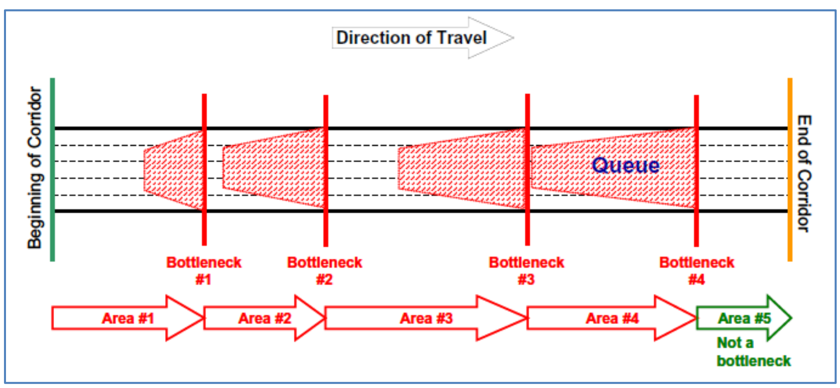


Figure 61 – Bottleneck Area Segmentation Approach

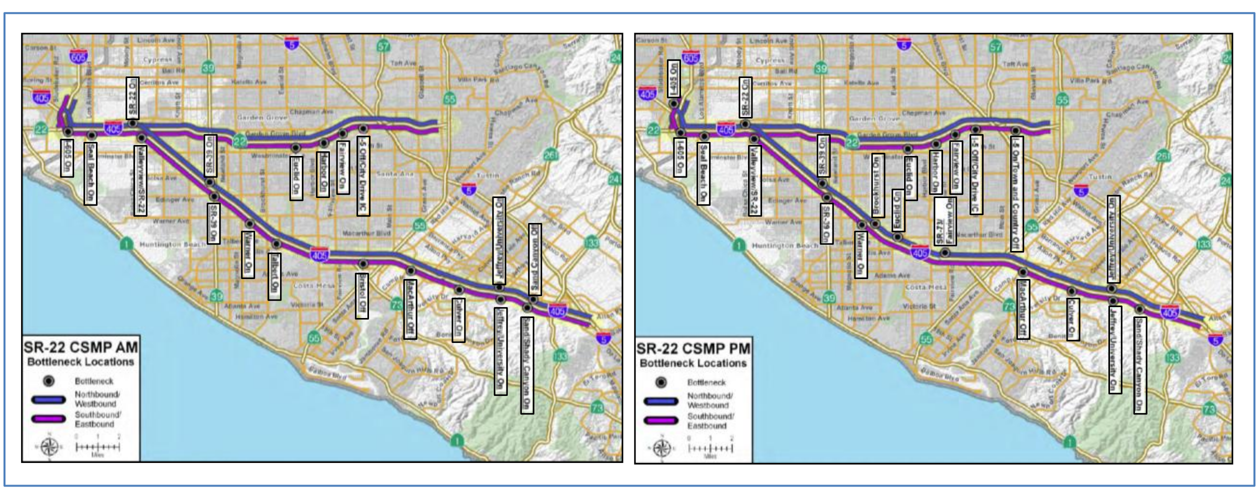


Figure 62 – Bottleneck-Based Segmentation Example – I-405/SR-22 Corridor

5.14.2. POST-SIMULATION DATA PROCESSING NEEDS

While simulation tools offer many built-in reporting capabilities, all CSMP operational evaluations required post-simulation data processing to extract performance measures of interest and prepare data for inclusion in technical memos and final project reports. Examples of post-simulation data processing include:

- Processing of simulation output data to obtain performance measures not included in standard simulation outputs. For instance, simulation models typically assess delays relative to the free-flow speed or speed limit. Caltrans, however, typically assesses delay against a 60-mph reference speed. Post-simulation data processing was therefore required for most corridors to extract 60-mph delays from estimated link speeds or travel times.
- Aggregation of performance measures across individual links to develop segment-specific measures (see example of Figure 50). Most simulation models will output performance measures for individual links. Unless built-in or plug-in functions exist to automatically aggregate data across predefined sets of links, data post-processing will be required to obtain aggregated performance measures for segments or sections covering multiple links.
- Aggregation of performance measures across successive links and time periods to develop speed contour maps (see examples of Figure 51and Figure 52).
- Mapping of congestion hotspots.
- Development of tables, typically using Microsoft Excel, compiling statistics from individual scenarios or comparing statistics across multiple scenarios.

5.14.3. PERFORMANCE METRICS FOR INITIAL CORRIDOR PERFORMANCE ASSESSMENT

Table 35 lists the performance measures that were considered for the initial performance assessment of each corridor. For the I-5, I-805 and I-405/SR-22 corridors, the initial assessment exclusively relied on a compilation of data from PeMS traffic sensors, HICOMP reports, probe vehicle runs and other field sources. For the I-80, US-101 and I-205/I-5 reports, performance measures related to safety, preservation and productivity were exclusively obtained from field data. However, simulation results were considered in addition to field data to compile mobility and productivity measures.

5.14.4. PERFORMANCE METRICS FOR ASSESSING IMPROVEMENT SCENARIOS

Table 36 compiles for each corridor the performance measures that were extracted from simulation model outputs to evaluate the impacts and benefits associated with the various improvement strategies considered. For each corridor, most of the performance measures listed in the table have also been previously used to conduct the initial corridor performance and causality assessment. The following subsections summarize key observations from the data of Table 36.

5.14.4.1. Corridor mobility

Traffic simulations were predominantly used to compile mobility measures. All CSMP reports compare statistics on vehicle-hour of delays incurred within each corridor across various scenarios. While average travel speeds and travel times were likely outputs from the simulations and used to compile the reported delays, these performance measures were not always included in the final reports.

Table 35 – Performance Measure Compiled for Current Performance Assessment

Category	I-80 West	US-101	I-5	I-205 / I-5	I-805	I-405/SR-22
Freeway Performance						
Mobility	• 35-mph threshold VHD by direction, day of week, time of day • Speed profiles/ contours	• 24-hour VHD, by segment • Average travel times, by peak period • Average system speed, by direction, peak period, facility (mainline, HOV)	• 35-mph threshold VHD, by segment (*HICOMP data* only) • 60-mph threshold VHD, by year, month, day of week, time of day, severity • Average travel time, by time of day • Speed profiles/ contours	• 60-mph threshold VHD, by segment, time of day • Travel times by segment, time of day • Speed profiles	• 35-mph threshold VHD, by segment (*HICOMP data only*) • 60-mph threshold VHD, by year, month, day of week, time of day, severity • Average travel time, by time of day • Speed profiles/ contours	• 35-mph threshold VHD, by segment (*HICOMP data only*) • 60-mph threshold VHD, by year, month, day of week, time of day, severity, facility type (mainline/HOV) • Average travel time, by time of day, facility type (mainline/HOV) • Speed profiles/ contours
Productivity	• Lost lane-miles by direction, time of day • VMT, by direction, month • VHT, by direction, month	• Lost lane-miles, by segment, direction • Congested lane-miles by segment, direction • VMT and PMT, by direction, peak period, facility (mainline, HOV) • VHT and PHT, by direction, peak period, facility (mainline, HOV)	• Lost lane-miles, by direction, year, time of day	• Lost lane-miles, by segment, time of day • VMT, by direction, time of day	• Lost lane-miles, by direction, year, time of day	• Lost lane-miles by direction, year, time of day, facility type (mainline/HOV)
Reliability	Average and 95th percentile travel times, by time of day	• Average and 95th percentile travel times, by segment, peak period • Buffer index, segment, peak period	• Average and 95th percentile travel times, by time of day	• Average and 95th percentile travel times, by time of day • Buffer index, by time of day	• Average and 95th percentile travel times, by time of day	• Average and 95th percentile travel times, by time of day
Safety	• Number of accidents by segment • Accident rate by segment		• Number of collisions, by month, day of week	• Number of collisions, by segment • Accident rate by segment • Number of incidents by milepost and type	• Number of collisions, by month, day of week	• Number of collisions, by month, day of week, severity
Preservation	• Distressed lane-miles • International Roughness Index (IRI) by milepost		• Distressed lane-miles • International Roughness Index (IRI) by milepost		• Distressed lane-miles • International Roughness Index (IRI) by milepost	• Distressed lane-miles • International Roughness Index (IRI) by milepost
Arterial Performance						
Mobility	• Average travel time and speed, by segment • Average number of stops and stop duration, by segment • LOS, by intersection			• Level of service, by intersection		

Table 36 – Primary Performance Measures Extracted from Simulation Models

Performance Measure	I-80 West	US-101	I-5	I-205 / I-5	I-805	I-405/ SR-22
Mobility						
Vehicle hours of delays (VHD)	●	●	●	●	●	●
Person hours of delay (PHD)		●				
Average segment speeds	●		●	●		
Average segment travel times	●		●	●		
Bottleneck locations		●	●		●	●
Productivity						
Vehicle miles traveled (VMT)		●	●			
Person miles traveled (PMT)		●				
Vehicle hours traveled (VHT)		●	●			
Person hours traveled (PHT)		●				
Lost lane miles		●				
Q Ratio (VMT/VHT)		●				
Level of service (LOS) - Intersections	S			●		
Level of service (LOS) - Corridor				●		
Reliability						
Buffer Index		●				
Safety						
Annual collisions		E				
Traffic demand Impacts						
Change in link volumes	●					
Project Benefits/Costs						
Benefit/Cost ratio	●		●		●	●

S = Evaluation using Synchro
E = Accident rates forecasted based on simulation results

Mobility measures can be compiled on a vehicle or person basis. While vehicle-based measures were provided for all corridors, person-based measures were only compiled for the US-101 corridor. The estimates were produced directly by FREQ 12 based on vehicle occupancy data inputted into the model. Simulation tools used to evaluate other corridors also had the capability of reporting person-based statistics. For instance, Paramics, VISSIM and TransModeler all include a parameter defining the average occupancy of each vehicle type. Why person-based statistics have not been compiled is likely the result of an age-old tendency to consider only vehicle-based statistics for operational evaluations that do not involve transit systems or strategies seeking to induce mode shifts. Finally, while the I-80 corridor model simulated buses, these vehicles were only included to accurately replicate their utilization of HOV lanes.

5.14.4.2. Corridor productivity

Lost lane-miles were only included in the final CSMP report for the US-101 corridor. While many of the reviewed simulation outputs for the other corridors included basic productivity measures such as VMT and VHT, these measures were not used to formally report the impacts of the various improvement strategies on corridor performance in the final CSMP documents.

One reason that has been mentioned during interviews for not reporting VMT and VHT measures is the difficulty of producing reliable estimates of traffic demand for future year scenarios, particularly scenarios looking 10 or 20 years into the future. Significant projected traffic growth can further lead to a situation in which the modeled network is unable to process all the modeled demand. When this occurs, vehicles unable to enter the network will artificially queue at the edge of the network. Depending on the simulation model, the delays incurred by these vehicles may or may not be included in the reported performance statistics. Following the implementation of an improvement project, increases in VMT or VHT within the simulation model may not necessarily reflect an increase in traffic demand, but simply that fewer vehicles may be queuing at the edge of the network.

Only a few evaluations compiled a level of service (LOS) metrics similar to those found in the Highway Capacity Manual. In most cases, LOS values were only provided for signalized intersections. Depending on the case, these values were either estimated from simulation results or, in the case of signalized intersections, developed through a separate analysis using the Synchro software.

5.14.4.3. Travel time reliability

While it is theoretically possible to estimate the range of possible travel times along a corridor by using the results from a number of simulation runs initiated with different random number seeds, impacts on travel time reliability were not assessed for any of the corridors using microscopic simulation models.

Potential impacts on reliability were only evaluated for the US-101 corridor, which conducted evaluations using the FREQ 12 macroscopic model. However, the reliability assessments that were conducted for this corridor are only indirectly based on simulation results. Since FREQ 12 is a deterministic model, it always produce the same results for a given scenario under a given travel demand and operating conditions. To assess changes in reliability, current travel time variability along the corridor was determined using trip data collected from electronic toll tag readers. Regression equations were then developed to forecast the 95^{th} percentile and standard deviation of corridor travel times based on the length and mean travel time of each freeway section. Future year reliability was then predicted for each scenario by inputting the mean travel time estimated by FREQ 12 in the regression equation.

5.14.4.4. Impacts on Route Selection

While a number of corridors modeled parallel arterials, none of the developed models were employed to assess the impacts of proposed improvements on route selection. The only corridor for which a route diversion study was conducted is the I-80 corridor. However, while the I-80 Paramics model includes a full modeling of a major arterial running parallel to the freeway, the route diversion analysis was conducted by analyzing travel patterns using the regional travel demand model covering the corridor. While there was an effort to calibrate the model with the dynamic route assignment option enabled, the modeling team was not able to get close to the established calibration targets within a reasonable amount of time. Since there was no confidence that the model could adequately simulate route choices, it was then proposed to do the evaluation using a feature from the regional travel demand model allowing individual ramp outputs to be constrained to represent the operation of ramp meters.

5.14.4.5. Safety assessment

Measures assessing impacts on safety are generally absent due to the collision-free nature of traffic simulation models. Situations that would result in vehicles colliding in reality are simply ignored. For instance, some models can tolerate that two vehicles partially occupy the same space. Other models instead arbitrary reposition vehicles or temporary allow unrealistic driver behavior to prevent two vehicles from colliding. The US-101 corridor is again the only one for which simulation data were used to forecast the safety impacts of proposed improvement projects. In this case, future safety performance was assessed by using forecasted growth in VMT and current accident rates per vehicle-mile to assess future accident rates on various network links.

5.14.4.6. Pavement preservation needs

Performance measures related to pavement preservation were not assessed for any of the corridor. While it is recognized that simulation models evaluate traffic performance on a virtual road network, vehicle counts could have been used to develop loading factors and forecast pavement degradation.

5.14.5. ASSESSMENT OF IMPROVEMENT COSTS

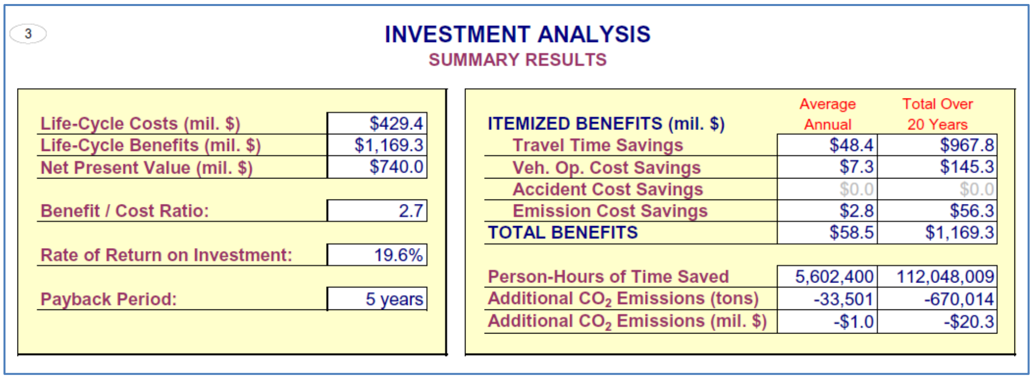
Project costs were estimated for all reviewed corridors. Estimated costs typically included both construction and operations/maintenance costs. Costs for projects already programmed and funded could generally be obtained from project planning and programming documents produced by Caltrans or regional transportation planning organization. Costs for some proposed projects could also be developed from preliminary studies conducted prior to the CSMP operational evaluations. For projects for which cost estimates were not available, estimated costs were in many instances obtained by reviewing similar completed projects. Evaluation of projects along the US-101 corridor went a step further by having a civil engineering consultant conducting field investigations and preparing schematic layouts of the proposed projects at a level that would allow preliminary costs to be estimated.

5.14.6. ASSESSMENT OF COST-EFFECTIVENESS

As indicated in Section 2.7.6, various analysis techniques can be considered to compare the cost-effectiveness of proposed improvements projects. The two most common techniques include:

- **Cost-Benefit Analysis (CBA)** – Technique attempting to monetize and compare the economic advantages and disadvantages associated with a particular project, with the objective of assessing either the project's net benefit or a project benefit/cost ratio.
- **Cost Effectiveness Analysis (CEA)** – Technique attempting to find the alternative minimizing the costs of achieving a desired result. It is often applied when the objectives of a project have been identified and the only remaining question is to find the least cost–option to arriving at these objectives, or for projects for which some benefits can be difficult to monetize.

A formal cost-benefit analysis was conducted for only three or the six reviewed CSMP corridors. The other corridors generally conducted only informal cost-benefit assessments. For all corridors for which a formal benefit-cost analysis was conducted, version 4.0 of the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) (System Metrics Group and Cambridge Systematics, 2009) was used to perform the analysis. As indicated earlier, Cal-B/C is an Excel-based spreadsheet tool structured to analyze several types of transportation improvement projects within corridor where a highway facility or transit service already exists. The tool calculates benefits over a 20-year life cycle for existing traffic, induced traffic, and traffic that may be diverted from a parallel highway or transit service. Peak and off-peak benefits are also estimated separately, as well as highway impacts for HOV passenger cars, non-HOV passenger cars, and trucks.



INVESTMENT ANALYSIS
SUMMARY RESULTS

Life-Cycle Costs (mil. $)	$429.4
Life-Cycle Benefits (mil. $)	$1,169.3
Net Present Value (mil. $)	$740.0
Benefit / Cost Ratio:	2.7
Rate of Return on Investment:	19.6%
Payback Period:	5 years

ITEMIZED BENEFITS (mil. $)	Average Annual	Total Over 20 Years
Travel Time Savings	$48.4	$967.8
Veh. Op. Cost Savings	$7.3	$145.3
Accident Cost Savings	$0.0	$0.0
Emission Cost Savings	$2.8	$56.3
TOTAL BENEFITS	$58.5	$1,169.3
Person-Hours of Time Saved	5,602,400	112,048,009
Additional CO_2 Emissions (tons)	-33,501	-670,014
Additional CO_2 Emissions (mil. $)	-$1.0	-$20.3

Figure 63 – Cal B/C Analysis Output Example (I-805 CSMP, Scenario 3A)

As an example, Figure 63 illustrates the Cal B/C output for one of the I-805 corridor scenarios. Similar outputs were obtained for the other corridors. Outputted economic measures include life-cycle costs and benefits, net present value, a benefit/cost ratio, an estimated rate of return on investment, and an estimated payback period. Monetized benefits from reduced travel times, reduced vehicle operating costs (fuel and non-fuel costs), fewer accidents, and reductions in vehicle emissions are also provided. While saving attributed to a reduction in accident frequency can also be obtained, such benefits were not always assessed due to the difficulty of predicting future accident rates. For one corridor, safety benefits were developed by simply assuming that proposed improvements would yield a 5% reduction in primary accidents and 10% reduction in secondary accidents.

5.15. PRIORITIZATION OF IMPROVEMENTS

Table 37 summarizes the criteria that were considered to prioritize the implementation of improvement projects, as well as the primary findings and recommendations from the evaluations. Key observations from the data presented in the table include:

- Benefit/cost ratios were the primary prioritization factor for the I-5 North, I-5 South, I-805, I-405 and SR-22 corridors. For each corridor, there is no formal recommendation whether and when a project should be implemented. This decision is left to the decision-makers to whom the CSMP report is destined. Each report simply highlights projects having a high benefit/cost ratio as being more desirable, under the caveat that elements external to the study, such as regional transportation development goals, may affect whether or when a specific project should be implemented.
- For the US-101 corridor, all evaluated projects were deemed needed. A prioritized implementation schedule was developed based on the ability of each project to reduce congestion along the freeway mainline, with projects having the greatest impact recommended to be implemented first.
- For the I-205/I-5 corridor, prioritization is based on the ability of each project to address identified deficiencies, its approval/design status, and its funding requirements. Only programmed or already planned projects were considered for the 2014 horizon. Recommended projects for 2024 include high-cost capacity improvements that would address major freeway deficiencies projected to exist by that time, while longer-term improvements include freeway capacity and interchange improvements that would not be required by 2024 but that can produce significant benefits by 2030.

Table 37 – Summary of Improvement Recommendations from Reviewed Corridors

Corridor	Prioritization Criteria	Study Findings/Recommendations
I-80 West	• Funding status/requirements • Design status • Extent of physical work required	• Recommended projects for 2015 only include projects that have secured funding, obtained environmental clearance, are under design, or do not require significant physical work or funding. These include construction of an eastbound HOV lane from SR 4 to the Carquinez Bridge and implementation of the I-80 ICM project. • Recommended improvements for the 2015-2020 period include projects that already have support and would require minor or moderate physical work or funding, but that have not yet acquired funding and obtained environmental clearance or completed their design. This includes enhancing proposed ICM capabilities, minor to moderate improvements to the freeway and arterial network, improved connectors between roadways, signalization of interchange intersections, and increase in public transit service. • Improvements over the 2030 horizon were not formally evaluated using simulation due to the high levels of congestion forecasted to exist at that time.
US-101	• Ability to reduce congestion along freeway mainline • Ability to obtain funding	• Due to the extent of existing and forecasted congestion, all capacity improvements considered were deemed needed. • A general recommendation was to implement first projects having the greatest impact on congestion along the freeway mainline (due to limitations with FREQ 12, evaluations did not consider potential benefits beyond the mainline). • Since it was assumed that funding would likely not be obtained to implement all the recommended 2015 improvements, any short-term capacity improvement project not implemented by 2015 was assumed to have top priority in the list of 2030 projects. Improvements considered in the two 2030 evaluation scenarios would only be implemented if sufficient funding is available to complete first the implementation of all the identified short-term projects. • Separate recommendations based on other studies were made for surface street and transit improvements. While prioritization for projects within each category, no prioritization was made across the various categories of projects.
I-5 North	• Benefit/cost ratio	• Implementing all improvements would reduce overall congestion on the corridor. Due to traffic growth, projected 2020 congestion would still be 35% above 2007 levels, but PM peak congestion would be 50% below 2007 levels. • Due to their high cost, HOV expansion projects only yield a benefit/cost ratio ranging between 1:1 and 2:1. However, improvements in mobility along the most heavily congested segments can be significant. In the southbound direction, improvements provided by the HOV lanes are negated by increases in delay where the lanes terminate, which prompts considering an extension of the facility. • Improvements to the Western Avenue interchange would produce small net benefits. However, this assessment does not capture benefits that may be achieved on the nearby local arterials. • Advanced ramp metering only brings modest mobility improvements on the corridor. • Operational improvements such as auxiliary lanes and ramp improvements, combined with advanced ramp metering, could result in additional mobility benefits of nearly $100 million. • Enhanced incident management strategies show promise at reducing incident-related delays. • Long-range capital improvements are expected to produce relatively modest improvements in mobility with a nominal benefit to cost ratio, primarily due to the $300 million estimated cost of the I-5/I-405 HOV lane connector project.

Table 37 – Summary of Improvement Recommendations from Reviewed Corridors (cont'd)

Corridor	Prioritization Criteria	Study Findings/Recommendations
I-5 South	• Benefit/cost ratio	• All evaluated projects were deemed beneficial for the corridor. • Implementing all improvements would reduce overall congestion by 2020 despite growth in traffic demand. Projected 2020 AM peak congestion would be 25% below 2007 levels, while PM peak congestion would be 20% below 2007 levels. • Programmed modifications to the Carmenita Interchange and construction of HOV lanes from the Orange County Line to I-605 would produce mobility benefits of nearly $1.5 billion and could improve mobility by over 50%. • Advanced ramp metering would only provide modest mobility improvements, likely due to lack of controlled connector metering at a major freeway-to-freeway interchange. • Operational improvements, such as auxiliary lanes and ramp improvements, combined with advanced ramp metering could result in additional mobility benefits of nearly $100 million. • Proposed I-710 interchange modifications and HOV lane extension from I-605 to I-710 may only deliver modest improvements, with gains in the northbound direction offset by worsening conditions in the southbound direction. • Enhanced incident management shows promise for reducing incident-related delays.
I-205/I-5	• Ability to address identified operational deficiencies • Relation to future development access • Funding requirements • Approval/design status	• All evaluated projects were deemed beneficial for the corridor. • Short-term recommendations are comprised largely of programmed projects expected to be completed by 2014 and RTP projects expected to be completed by 2017. • Recommended improvements for 2014 are comprised largely of high-cost, freeway capacity projects that would address major deficiencies projected to exist along the corridor by then. • Lower than anticipated congestion levels at the 2024 horizon suggested that the corridor could operate well without proposed HOV lanes on some sections of I-5 and without improvements to three interchanges. • Recommended improvements for the 2030 horizon primarily include freeway capacity and interchange improvements that the simulations indicated as not required by 2024 but that may produce significant benefits by 2030 or later.
I-805	• Benefit/cost ratio	• No improvement project was specifically rejected. • Implementing all short-term improvements would reduce congestion by more than 50%, due to improved mobility on the mainline, ramps, and arterials, with three of the four projects considered yielding benefit/cost ratios greater than 4.5:1. • The southern corridor HOV project would yield low returns is since a significant portion of the existing congestion would be relieved by the proposed auxiliary lane project at the H Street/Bonita interchange. Despite this low return, this project is still deemed needed since it will become part of the managed lanes system to be delivered by 2020. • As auxiliary lane projects are expected to be delivered by 2011, it is recommended to wait to see how these will relieve congestion before programming HOV extensions. If congestion in the southern part is sufficiently relieved, the northern HOV project should be implemented first. If not, new simulations should be executed to assess the best course of action. • Completion of the northern and southern managed lanes will reduce projected 2020 congestion by a third. Due to its high cost, this project only yields a benefit/cost ratio of 1:1. However, actual project benefits may be greater since benefits to transit riders are not included, as well as revenues that may be generated from the managed lane system. • The implementation of advanced ramp metering shows and construction of auxiliary lanes at the El Cajon interchange also shows excellent potential and should be considered for funding. • Enhanced incident management shows promise for reducing incident-related delays, with a benefit/cost ratio of 4:1.

Table 37 – Summary of Improvement Recommendations from Reviewed Corridors (cont'd)

Corridor	Prioritization Criteria	Study Findings/Recommendations
I-405	• Benefit/cost ratio	• No improvement project was specifically rejected. • Operational projects completed in the two years preceding the study have produced immediate results, with a benefit/cost ratio of 12:1. • The construction of HOV direct connectors would produce large benefits for a lost cost, with an overall benefit/cost ratio of 3.5:1. • HOV conversion to continuous access would produce large benefits for a low cost. • Auxiliary lane improvements at the corridor's south end would yield a benefit/cost ratio of 10:1. • Enhanced incident management shows promise for reducing incident-related delays. • Other improvements have low to moderate cost-effectiveness. Low-cost improvements, such as advanced ramp metering with connector metering, seem to be relatively reasonable investments. However, Caltrans needs to consider other factors, such as intangibles, for the high-cost investments.
SR-22	• Benefit/cost ratio	• No improvement project was specifically rejected. • Reconstruction of the eastbound collector-distributor facility along, which includes access improvements to the I-5 and SR-57 freeways, would be very cost effect (benefit/cost ratio of 9:1). • HOV direct connectors would produce a benefit/cost ratio of over 2:1, with benefits exceeding $670 million. • Advanced ramp metering with connector metering only yields modest mobility improvements. • Enhanced incident management shows promise for reducing incident-related delays.

- For the I-80 corridor, funding requirements, design status, and extent of required physical work were considered as prioritization criteria. Projects already approved, fully funded, already under design, or requiring little physical work were considered for short-term implementations (2015-2020 period). Mid-term project further favored projects addressing forecasted congestion and requiring relatively little physical work.

Overall, operational benefits derived from simulations results were used in all corridors to help determine the most effective projects, and in some cases, provide recommendations on when specific projects should be implemented. Final decisions on which project to implement were generally left to the decision-makers. Projects producing the highest benefit/cost ratio or having the largest potential to reduce queuing and congestion were generally placed high in the list of recommendations. In some cases, projects that had been found not to be required by a certain year were recommended for later implementation. There was finally no example of projects being removed from consideration as a result of a lack of impacts on corridor operations.

5.16. PRESENTATION OF EVALUATION RESULTS

Presentation of evaluation results typically involved the development of tables, graphs and maps. Various examples extracted from CSMP documents were shown throughout this section. In most cases, the development of these tables, graphs and maps required some post-simulation data processing. In some cases, some of the data processing was executed by plug-in modules specifically designed to extract and report performance measures (See Section 5.12).

Animation capabilities offered by the simulation tools were further used in several cases to develop movie clips for meetings with decision-makers and/or public presentations. Movie clips allow an audience to "see" how traffic may behave along a corridor or a specific location under a given set of circumstances. They could easily be produced for corridors using Paramics, VISSIM and TransModeler, as these three tools have built-in movie capture functions.

The movie clips that were developed range from clips simply capturing vehicles movements along bare road network to clips including detailed representation of the surrounding environments. Figure 64 shows a simple clip that was developed for the I-805 CSMP and which only shows the simulated roadways, vehicles and traffic control devices that were built-in within TransModeler. Figure 65 shows a Paramics movie clip that was prepared for the SR-57 CSMP that also includes buildings, trees, guardrails, and other physical elements. Figure 66 finally shows a clip prepared for the I-405/SR-22 CSMP presenting side-by-side traffic conditions under two different scenarios.

Figure 67 further illustrates a graphical representation of costs and operational benefits that has been used in a number of CSMP reports to help communicate evaluation results to decision-makers. The example illustrates the 20-year assessed life-cycle costs (red bars) and benefits (green bars) for the seven improvement scenarios that were evaluated for the I-405 corridor. The figure easily allows assessing the relative benefits and costs provided by each scenario, and more importantly, the fact that the scenarios providing the highest net benefits (benefits minus costs) are not necessarily the most cost-efficient. In this example, scenario S5/S6 produces the highest net residual benefits when subtracting deployment costs. However, when considering the benefit/cost ratios, listed at the top of the diagram, scenario S7/S8 is the most cost efficient alternative. While this scenario provides relatively small net benefits, these benefits are obtained for a very small cost, thus yielding a high benefit/cost ratio.

Figure 64 – TransModeler Movie Clip Screenshot (I-805 CSMP)

Figure 65 – Paramics Movie Clip Screenshot (SR-57 CSMP)

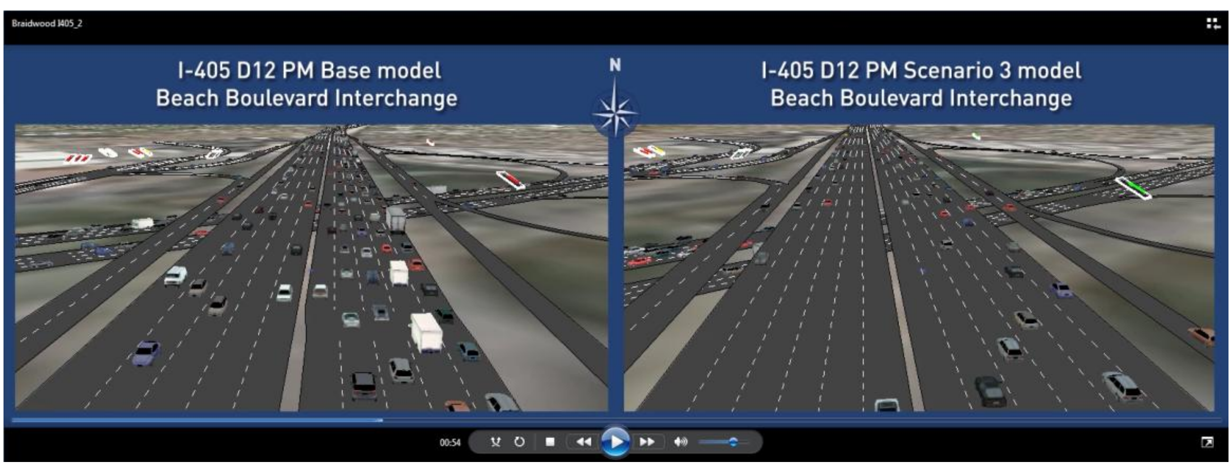


Figure 66 – Side-by-side Clips Highlighting Scenario Differences (I-405 CSMP)

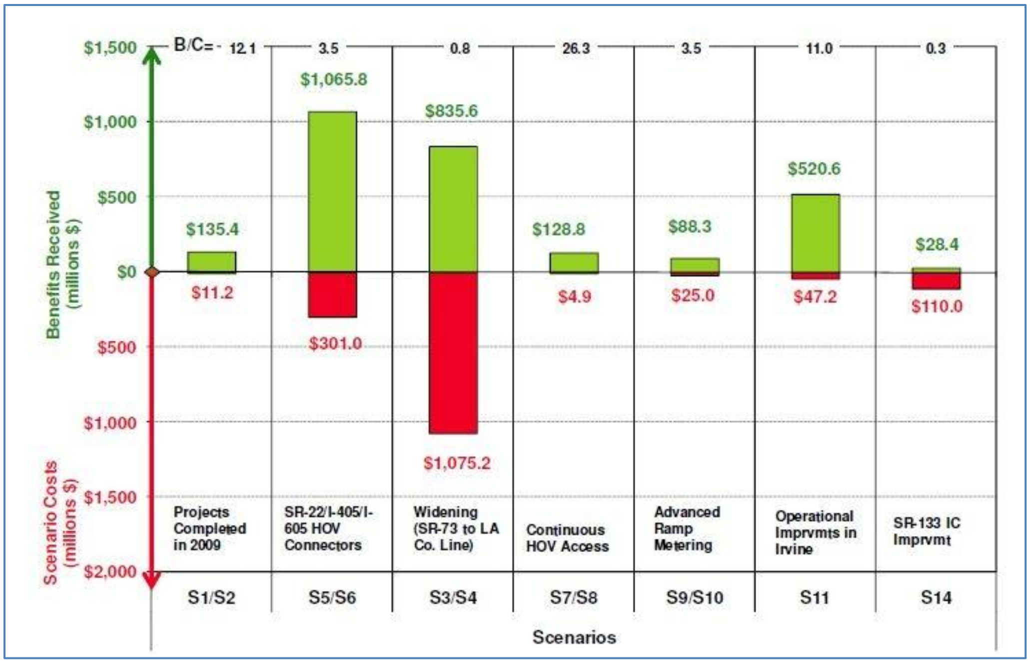


Figure 67 – Example of Comparative Assessment of Benefits and Costs of Improvement Projects

5.17. IMPACTS OF MODELING EFFORTS ON CORRIDOR EVALUATIONS

Simulation results were used to prioritize improvements, suggest implementation schedules, and help design proposed improvements. For some corridors, the results were also used to justify previously approved projects. Below is a summary of how simulations influenced the selection of improvements across the reviewed corridors:

- **I-80 West** – In addition to demonstrating the potential benefits associated with proposed ramp metering, variable advisory speed limit and lane management systems, simulation results were used to refine the design of the various systems considered.
- **US-101 San Mateo** – The simulation results justified all the proposed improvements and helped determine an implementation schedule. Projects having the greatest potential to reduce congestion were generally recommended to be implemented first, and those having the smallest impact to be implemented last.
- **I-5 Los Angeles** – Simulation results were used to determine the benefits and calculate a benefit/cost ratio associated with each proposed improvement bundle.
- **I-205/I-5 San Joaquin** – The simulation results were used to justify some previously approved projects and to determine an implementation schedule. For instance, the simulations identified several projects proposed for 2024 that would likely have a limited impact on congestion as a result of interactions with other improvements. A recommendation was thus made to delay these projects until 2030, when the simulations indicated they would carry a positively effect.
- **I-805 San Diego** – Simulation results were used to determine the benefits and calculate a benefit/cost ratio associated with each proposed improvement bundle.
- **I-405/SR-22/I-605 Orange County** – Simulation results were used to determine the benefits and calculate a benefit/cost ratio associated with each proposed improvement bundle.

6. TIME AND COST REQUIREMENTS OF CSMP MODELING EFFORTS

This section presents a summary analysis of the time and funds that were expended for the execution of CSMP simulation evaluations. Topics covered in this section include:

- Identification of the corridors considered for analysis;
- Analysis of the overall project duration;
- Analysis of the project costs; and
- Analysis of the impacts of select corridor characteristics on costs.

6.1. DATA SAMPLE

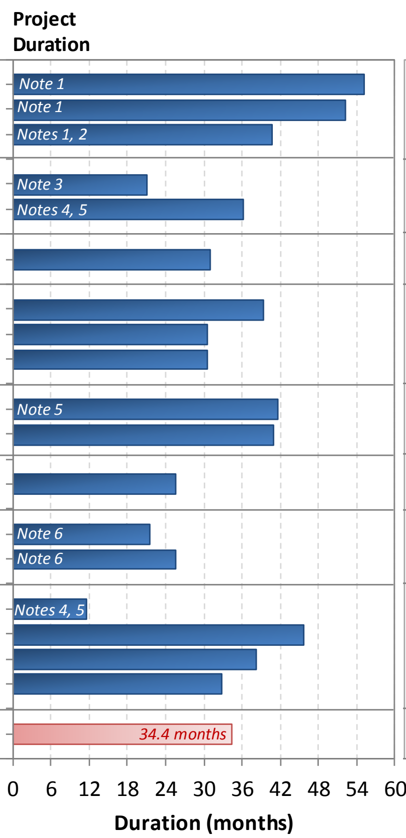
Project duration and cost analyses were not restricted to the six corridors of Section 5 for which a detailed review was conducted. All corridors for which relevant information could be retrieved and adequately compiled were considered. While it was initially expected that information could be obtained for most CSMP corridors, this task was hindered by the fact that various CSMP project teams used different data recording practices. Some corridors also featured incomplete model efforts, either because the effort was abandoned due to significant calibration difficulties or because a decision was made to model only a portion of the corridor. Due to their partial modeling efforts, data from these corridors were not considered. Overall, the information gathering effort led to the identification of 18 corridors, out of the 31 corridors listed in Table 2 in Section 2.4, for which reasonably reliable time and cost information could be retrieved.

6.2. OVERALL PROJECT DURATION

Figure 68 presents the recorded durations of each of the 18 CSMP corridor projects that were retained for the time and cost analysis. For each corridor, the reported duration includes the time assigned to collect data, process the collected data, develop and calibrate the simulation model, conduct peer reviews, develop evaluation scenarios, and evaluate operational improvements associated with each scenario. The statistics also include the time to complete the CSMP report after the simulation work was completed. The last entry on the diagram presents the average for all the listed corridors.

For all corridors except those in District 3, the statistics presented in Figure 68 correspond to modeling and evaluation efforts that were conducted prior to the publication of the corridor's CSMP report. For the District 3 corridors, the statistics include modeling efforts that were completed after the publication of the CSMP report. For these corridors, while the modeling was initiated prior to the writing of the report, unanticipated delays in model development led the CSMP evaluation teams to develop initial improvement recommendations without using simulation results. The modeling efforts were nevertheless considered part of the CSMP operational evaluations since the development of microscopic simulation models for conducting future evaluations was a recommendation of the evaluations.

Across all reviewed corridors, the data in Figure 68 indicates that the completion of a simulation-based CSMP study, from its initiation to the submittal of the final CSMP report, typically took between 24 and 42 months, with an average of slightly over 34 months, or nearly 3 years. The shortest effort was for the I-5 corridor in District 12, which only took 12 months to complete, while the longest effort was for the US-50 corridor in District 3, which took 55 months to complete. Since the I-5 CSMP is the latest to have been completed, it is believed that this project has largely benefited of the growing body of knowledge on sound modeling practices and corridor evaluation procedures that have been developed from previous corridor evaluations. It is therefore anticipated that future simulation-based corridor evaluations will have a shorter average duration, provided that the knowledge and practices that have been developed are not be lost due to a long period of inactivity.



District	Corridor	Project Duration	Corridor Length	Models Developed	Interchanges	Scenarios Evaluated (AM + PM Peak)	Simulation Model(s)
District 3	US-50	Note 1	50 mi	2 [a]	39	14 [e]	Paramics
	I-80/SR-51	Note 1	48 mi	1	33	10	Paramics
	SR-65/80	Notes 1, 2	33 mi	1	14	16	Paramics
District 4	I-580/I-238	Note 3	36 mi	2 [a]	21	16 [e]	Paramics
	I-880	Notes 4, 5	42 mi	1	30	22	Paramics
District 5 & 7	US-101		50 mi	1	39	10	TransModeler Hybrid
District 7	I-5 N/I-5 S		41 mi	2 [b]	49	52 [e]	VISSIM
	I-210		45 mi	1	44	32	VISSIM
	I-405 LA		36 mi	2 [c]	36	62 [e]	Paramics
District 8	SR-91	Note 5	22 mi	1	22	20	VISSIM
	I-10		45 mi	1	31	24	VISSIM
District 10	I-205/I-5		40 mi	1	35	26	CORSIM
District 11	I-5	Note 6	27 mi	1	27	8	TransModeler Hybrid --> Micro
	I-805	Note 6	29 mi	1	29	20	TransModeler Hybrid --> Micro
District 12	I-5	Notes 4, 5	44 mi	1	52	18	Paramics
	I-405/SR-22		41 mi	2 [d]	41	52 [e]	Paramics
	SR-91		15 mi	1	15	34	TransModeler
	SR-57		12 mi	1	12	32	
Average		34.4 months	36 mi				

Notes:
1 - Modeling efforts completed after publication of initial CSMP report
2 - Duration includes a multi-month delay in obtaining travel demand data
3 - Sketch planning analysis with travel demand models was used to evaluate some scenarios
4 - Duration does not include attempted modeling work on corridor prior to start of CSMP
5 - Project involved a switch in modeling team
6 - Project involved a change in modeling approach

a - Separate models developed for the western and eastern sections
b - Separate models developed for I-5 North and I-5 South
c - Separate models developed for I-405 and SR-22
d - Separate models developed for I-405 North and I-405 South
e - Total for both developed models

Figure 68 – Duration of CSMP Operational Evaluation Projects

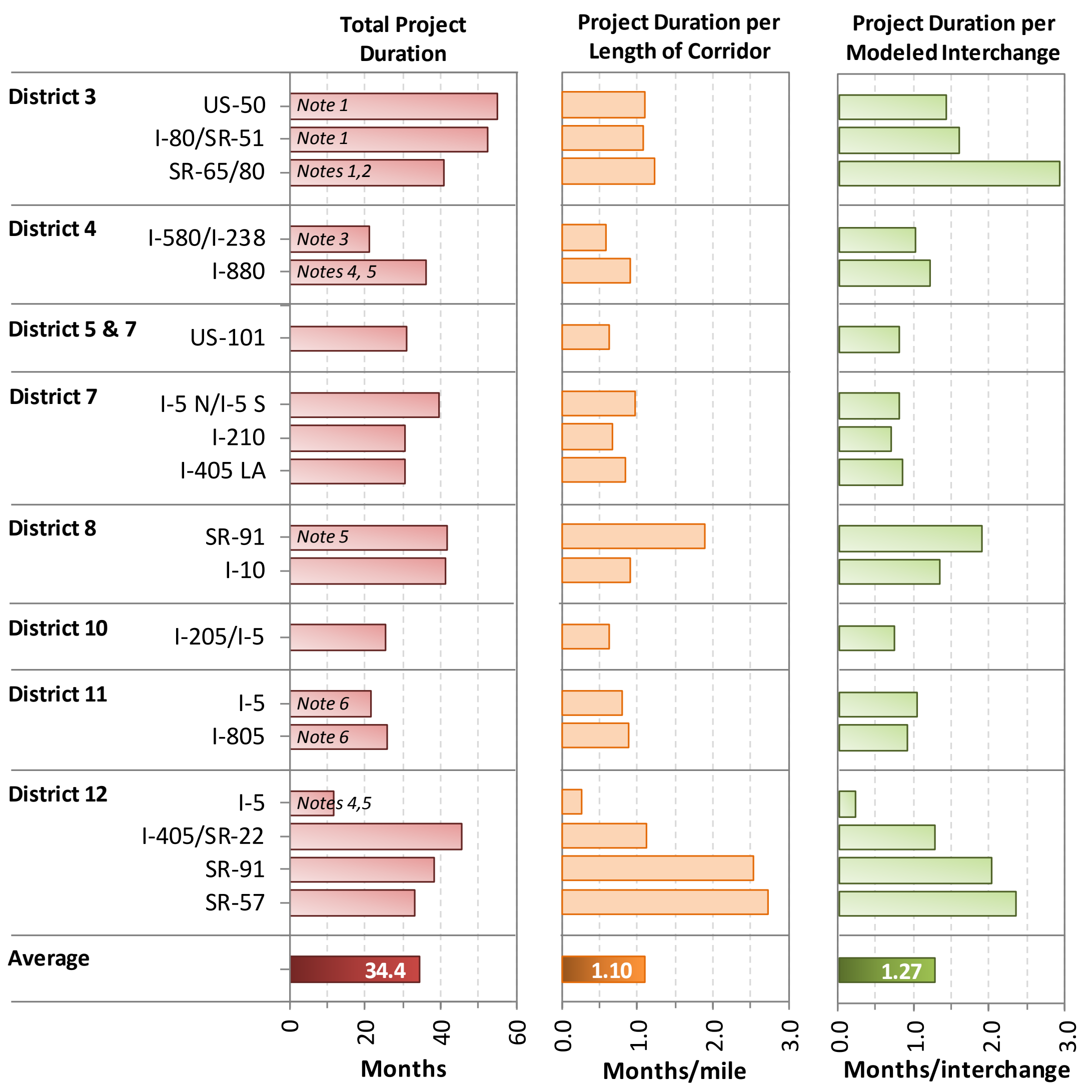
Several factors explain the observed variability in the time that was required to complete a CSMP, and more particularly in the time that was required to complete the development of both the simulation model and scenarios considered for evaluations:

- Differences in geographical scope, such as length of modeled freeway, extent of modeling of arterials crossing the freeway mainline, inclusion/exclusion of parallel arterials, etc.
- Differences in the complexity of road network within the corridor, such as proportion of linear and curved roadway segments, number of simple and complex interchanges, as well as the presence of HOV lanes, ramp meters, and other ITS applications.
- Previously developed model that can be used as a starting point for the modeling.
- Differences in data collection requirements due to differences in the quantity or quality of available data along the corridor.
- Number of bottlenecks and complex merging/weaving sections modeled.
- Expertise of the team in addressing complex modeling and calibration issues.
- Number and complexity of scenarios developed and evaluated (number of improvement projects modeled within each scenario, extent of modifications to the road network, need to develop custom features using the simulation tool’s Application Programming Interface, etc.).
- Expertise of the District review team in accepting only excellent modeling work.

To illustrate the impacts of corridor-specific elements on the time required for the model development and scenario evaluations, Figure 69 compares total project durations to the length of the modeled corridor and the number of interchanges to code. As can be observed, the corridors featuring the longest nominal simulation efforts were not necessarily those requiring the highest amount of time per mile of freeway or per interchange. Differences in corridor geometry and complexity, data availability, as well as the number and complexity of scenarios, are all factors that can explain the discrepancies between the total and prorated project durations. In one case, the compiled project durations included a long, unexpected delay in obtaining travel demand data. In other cases, the expertise of the modeling team in resolving development and calibration issues may also have been a factor.

It should be pointed out that two of the simulation efforts listed in Figure 68 featured a decision to switch the modeling approach (using TransModeler, from a hybrid microscopic/mesoscopic to microscopic only) due to persistent difficulties in obtaining a calibrated model. Furthermore, two other corridors featured a switch in modeling team. These changes were not without impact, as they involved a partial duplication of modeling activities. However, they also did not necessarily require a complete restart of the model development since the results of previous efforts, such as data collection and data preparation, could often be salvaged. In particular, the changes occurring in these four corridors did not push them to be the longest modeling efforts. The switches in modeling approach/team were generally made relatively early in the project. These early switches were thus less likely to add significant time and costs to a project than switches that would have occurred later.

Another observation concerns the I-880 corridor in District 4 and the I-5 corridor in District 12. Both corridors benefited from preliminary modeling attempts conducted by staff from the University of California at Irvine prior to the official start of the CSMP operational evaluations. In these cases, the time and costs expended on CSMP preparatory work by the University is not accounted for in the data compiled in Figure 68.



Notes: 1 - Modeling efforts completed after publication of initial CSMP report
2 - Duration includes a multi-month delay in obtaining travel demand data
3 - Sketch planning analysis with travel demand models was used to evaluate some scenarios
4 - Duration does not include attempted modeling work on corridor prior to start of CSMP
5 - Project involved a switch in modeling team
6 - Project involved a change in modeling approach

Figure 69 – Duration of CSMP Modeling Efforts as a Function of Corridor Characteristics

6.3. COST OF SIMULATION-BASED CSMP OPERATIONAL EVALUATIONS

Figure 70 summarizes the costs incurred for conducting the CSMP operational evaluations for the 18 corridors listed in Figure 68. Corridor-specific costs are not presented due to the difficulty of compiling reported expenditures within consistent categories. This issue arose from the use of various data recording practices across the considered projects. The figure presents instead the minimum, maximum and average costs that were incurred across the individual projects.

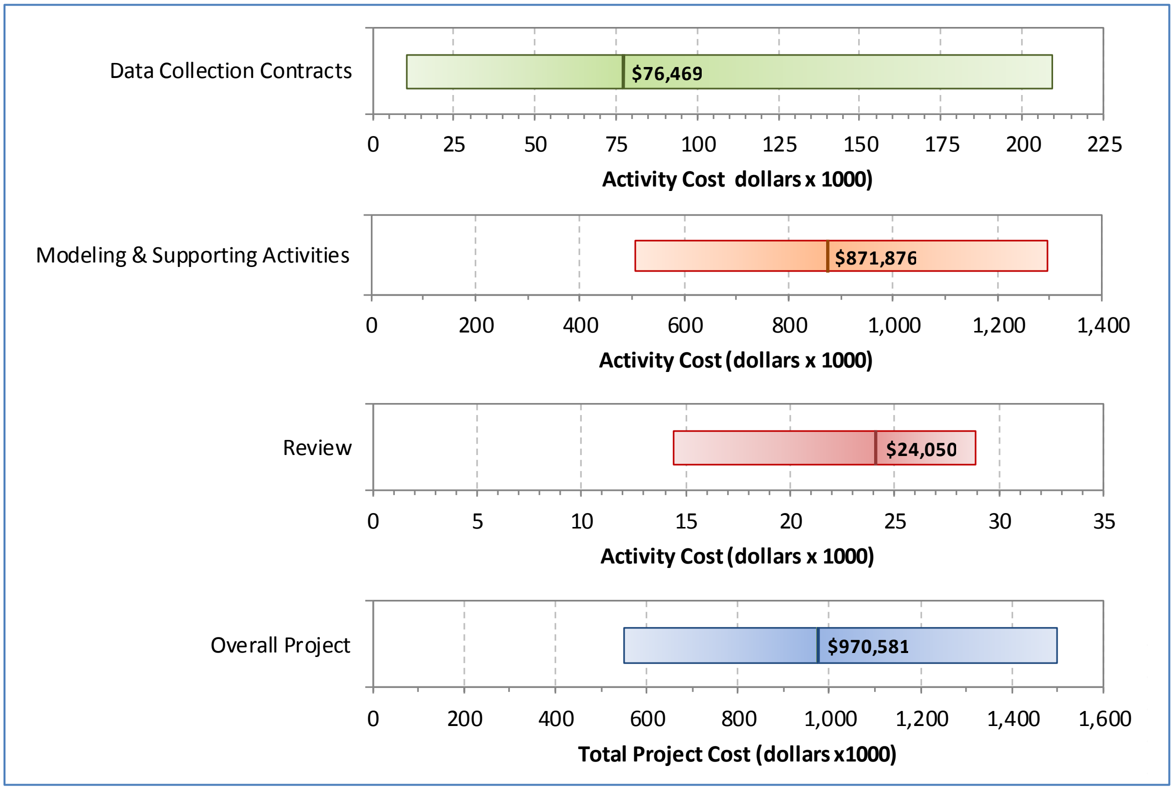


Figure 70 – Cost of CSMP Operational Evaluation Efforts

For each corridor, cost information was compiled from various documents, including task orders, project invoices and project reports, as well as discussions with individuals involved in the modeling and evaluation activities. The available information generally allowed for the categorization of costs along the following four broad categories:

- **Data collection contracts** – Costs for hiring a consultant to collect traffic volumes, travel time and other relevant data pertaining to the CSMP operational evaluations. Costs associated with the preparation of data for simulation model coding are not included here.
- **Modeling and supporting activities** – Costs associated with coding the road network and developing scenarios , as well as supporting activities, such as organizing data collection, identifying and developing scenarios, reviewing simulation results, conducting stakeholder outreach, promoting public engagement, and writing of the final CSMP report.
- **Consultant peer review** – Costs associated with the use of independent peer reviewers to assess the adequacy of the developed simulation models.
- **Overall project** – Total cost associated with the CSMP operational evaluations.

Among the reviewed efforts, the overall project costs ranged from $550,000 to $1.5 million, with an average of $970,000. When considering specific activities, between $10,000 and $209,000 were spent on data collection contracts, with an average slightly above $76,000, while between $14,400 and $28,900 were spent on peer-review, with an average of $24,000. Expenses directly related to the coding, calibration, and use of simulation models varied between $503,800 and $1.29 million, with an average of $871,900. Similar to project duration, several factors explain the range of observed costs and the difficulty in developing an average cost for each task that can be applied to all corridors.

It must be noted that the above figures do not include all the costs that were effectively incurred during the execution of simulation modeling efforts. The time spent by Caltrans District staff managing the CSMP operational evaluations and providing modeling support to the modeling consultants is not included as this information has generally not been documented. A formal cost evaluation should normally include these incidental elements. Information provided by some Caltrans District staff suggests that thousands of hours have been spent within individual districts to support the CSMP operational evaluations, which is not a negligible amount. Actual project costs are therefore expected to be somewhat higher than those shown in the figure.

While compiling costs associated with specific activities across individual corridors, the following general observations were made:

- As expected, modeling and simulation activities comprised the majority of the costs incurred on each project. Depending on the corridor, these costs accounted for between 80% and 96% of the overall project costs, with an average of 90%.
- Costs for data collection contracts were between 1.5% and 15.7% of the overall project costs, with an average of 7.8%. These percentages did not include costs associated with the need to process data from PeMS and existing counts, which was typically done by the modeling team.
- When factoring both the data collection and data processing efforts, the reported percentages dedicated to data collection were consistent with response statistics from the survey of modelers, project managers and decision-makers that was conducted as part of this project. In the survey, respondents indicated that data collection typically consumed between 5 and 33% of the overall modeling budget, with an average of 15%. While not specifically stated, the data collection statistics provided by many respondents likely included both data collection and subsequent data preparation activities.
- 14 of the 19 reviewed corridors used consultants as peer reviewers. For these corridors, expenses related to the peer-review activities accounted between 1.1% and 4.6% of the overall project costs, with an average of 2.0%. While these percentages are small, they still correspond to expenses totaling between $14,400 and $28,900 that should therefore not be overlooked.
- No review costs could be assessed for the models that were reviewed internally by Caltrans staff. This included 4 corridors: the I-880 and I-580 corridors in District 4, and I-5 and SR-91 corridors in District 12. For these models, the actual cost of the CSMP operational evaluations should therefore be slightly higher than what was reported in project documents.
- Project documents for the I-5/I-805 corridor indicate that $63,500 was spent on the development of API modules for the TransModeler model. These costs account for slightly over 3% of the overall project incurred costs. However, it should be noted that the APIs that were developed for this corridor were also used for the modeling of the I-805 corridor. Part of the costs could therefore technically be assigned to the other modeling effort.

- Several modeling efforts involved Paramics and VISSIM, and used plug-in modules that were developed by a third party under a separate contract within the CSMP umbrella. While these costs were not counted in the expenses related to each project, they can technically be apportioned across the various projects that employed the modules.

6.4. UNIT COST METRICS

Unit costs were often sought to support project planning activities. Examples of frequently sought unit costs for simulation modeling projects include cost per mile, per interchange, and per evaluation scenario. However, as was explained in Section 6.2, several factors often affect the overall cost for a particular corridor study. The real complexity of a project is therefore not commonly a function of single elements but rather of the combination of multiple elements. Consequently, it is relatively difficult to provide a narrow estimate of projected costs without conducting a detailed needs assessment.

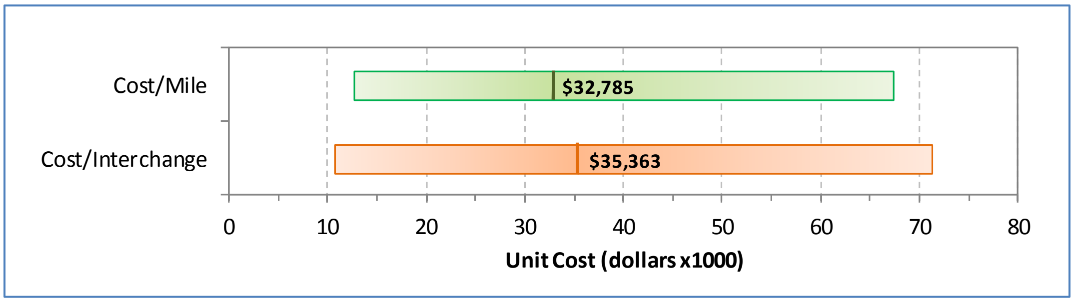


Figure 71 – Cost of CSMP Modeling Efforts as a Function of Corridor Characteristics

To illustrate the potential impacts of corridor-specific factors on overall costs, Figure 71 compiles unit project costs based on the length of the modeled corridor and number of interchanges coded. The illustrated statistics are only a few examples of unit costs that can be derived to assess the cost intensity of a project. As can be observed, this simple analysis yields significant variations in potential unit costs. The cost per mile across the 18 corridors analyzed ranged from $12,600 to $67,200, with an average of $32,700 and a median of $26,500. The cost per interchange further ranged from $10,700 to $71,200, with an average of $35,400 and a median of $33,200.

It was further observed that the projects with the highest overall costs were not necessarily those with the highest unit costs. A variety of factors again explained this observation, such as differences in data collection requirements, geographical scope, road network complexity, complexity of scenarios, and modeling team skill level. The above observation invites strong caution when attempting to develop a general metric for forecasting the cost of future modeling activities. While a general metric allow for a rough, ball-park estimate for preliminary project planning, the funds allocated to each simulation project should ultimately be assessed based on corridor-specific elements. It must also be considered that future studies may benefit from the availability of already developed models. Even though reutilizing previously developed models may require collected new data, as well as modifying and recalibrating the existing models to account for changes in geometry and traffic demand, the ability to start the evaluation process with an existing network should provide some time and cost savings when compared to starting a modeling effort anew. Improved modeling practices based on lessons learned from the current evaluations can also lead to more efficient modeling activities, and thus additional savings.

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7. MODELING EFFORTS IN SUPPORT OF USDOT ICM PROGRAM

Due to similarities with the CSMP operational evaluations, a review of the simulation modeling efforts conducted as part of the USDOT's Integrated Corridor Management (ICM) initiative was initiated in addition to the review of CSMP modeling efforts. The ICM initiative, which is still under way, seeks to demonstrate how Intelligent Transportation System (ITS) technologies can efficiently and proactively be used to manage the movements of people and goods along major transportation corridors. A key aim is to demonstrate the benefits that can be obtained by the development of improvement strategies combining various strategies, considering various modes of transportation, and promoting inter-jurisdictional cooperation. As can be observed, this is an objective that is not too different than the one behind Caltrans' CSMP development effort. Specific elements that are reviewed in this section include:

- ICM program overview;
- Corridor analysis approach;
- Simulation modeling approach;
- Geographical scope;
- Model calibration and validation;
- Test of modeling procedures on I-880 corridor;
- Modeling of demonstration corridors;
- Scenario development;
- Performance measures; and
- Documented lessons learned.

7.1. ICM PROGRAM OVERVIEW

The ICM Program followed a multi-phase approach to evaluate the potential effectiveness of the ICM concept. Phase 1 was completed in early 2006 and included research on the current state of corridor management in the United States, the identification of ICM-like practice examples around the world, and an initial feasibility assessment. A generic Concept of Operations was also developed to serve as a guidance document for sites seeking to develop their own ICM concept. Phase 2 was initiated in September 2006 and focused on the development of analytic tools and methods that would enable the evaluation of ICM concepts. Phase 3, which is currently under way, is conducting more in-depth evaluations of the ICM concept through three site-specific pilot implementations and evaluations.

Phase 3 of the project started with the selection of eight pioneer sites. Table 38 lists the sites that were retained and the ICM strategies that were considered for each one. A Concept of Operations and requirements documents were developed for each of the eight selected sites. Following a review of the operational concepts, three sites were further invited to participate in a second stage. These included the San Diego, Minneapolis and Dallas pioneer sites. The focus of this second stage was to conduct more detailed evaluations of potential benefits using simulation and analytical evaluation tools. Table 39 lists the strategies that were evaluated for each of the three remaining corridors in the second stage.

Following the completion of these simulation evaluations, the US-75 and I-15 corridors were retained for field demonstrations. These demonstrations are still in the implementation phase. Their primary goal of each implementation is to demonstrate the capability of the ICM concept to improve corridor performance. Another aim is to provide the documentation necessary to transfer the ICM concepts into practice.

Table 38 – Management Strategies Examined in Stage 1 of ICM Program

Corridor	Location	Freeway			Arterial	Bus			Rail		
		HOV Lanes	Tolling	Value Pricing	Real-Time Control	Fixed Route	Express Buses	Bus Rapid Transit	Commuter Rail	Light Rail	Subway/ Heavy Rail
US-75	Dallas, TX	●	●		●	●	●			●	
I-10	Houston, TX	●	●	●	●	●	●	●			
I-394	Minneapolis, MN	●	●	●	●	●	●	●			
I-270	Montgomery City, MD	●			●	●	●		●		●
I-880	Oakland, CA	●	●		●	●	●	●	●		●
I-10	San Antonio, TX				●	●	●				
I-15	San Diego, CA	●	●	●	●	●	●	●			
I-5	Seattle, WA				●	●	●		●	●	

Table 39 – Management Strategies Evaluated in Stage 2 of ICM Program

ICM Strategy	I-15	US-75	I-394
Traveler Information			
• Earlier dissemination and information sharing between agencies		●	●
• Comparative travel times (mode and route)			●
• Parking availability at park and ride lots		●	●
• Freeway traveler information (pre-trip and en-route)	●	●	●
• Arterial traveler information (pre-trip and en-route)	●	●	●
• Transit traveler information (pre-trip and en-route)	●	●	●
Traffic Management			
• Reduced incident times			●
• Incident signal retiming plans for arterials or frontage roads		●	●
• Retimed ramp meters for incidents or congestion			
• Coordinated signal and ramp meter operation	●		
• System-wide coordinated ramp metering			
HOT/HOV Lanes			
• HOT lane (congestion pricing)	●	●	●
• HOV lane (change minimum number of occupants)	●	●	●
• Open to SOV during incidents		●	
Transit Management			
• Dynamic rerouting			●
• Special events capacity expansion		●	●
• Arterial signal priority	●		●
• Freeway ramp signal priority			●
• Smart parking system for Light Rail Transit (LRT)		●	
• Add parking and valet		●	
• Physical priority to buses on arterials	●		

7.2. CORRIDOR ANALYSIS APPROACH

Figure 72 provides an overview of the recommended approach for evaluating the benefits of candidate operational strategies within each ICM corridor. The following list describes in more details the major steps in the recommended process (Cambridge Systematics, 2007; Alexiadis, 2008a):

1. **Kickoff meeting** – The analysis team responsible for each site was first to establish communication channels, protocols, and data and information sources; discuss the scope of work, schedule, and budget; and obtain a thorough understanding of the goals for the analysis. Appropriate performance measures and analysis tools were also to be selected.

2. **Data collection and analysis of existing conditions** – In this step, the analysis team was to collect and analyze all information necessary to understand existing traffic conditions in the study area, and identify specific causes of problems. The collected data were to be used to determine the causes of existing recurrent traffic congestion problems within each corridor. Locations of freeway bottlenecks were to be identified, as well as other locations that may constitute mobility constraints, such as freeway ramps or arterial intersections. The data were also to be analyzed to quantify the magnitude of non-recurrent congestion in the corridor. The data to be collected included more specifically:
   - *Geometric roadway data* – Number of lanes on the freeway and parallel arterials; and basic geometric information, such as lane and shoulder widths, transit service, and configurations of key intersections on parallel arterials.
   - *Existing performance data* for all modes, including peak-period traffic volumes on the freeway and parallel arterials, vehicle occupancies, traffic volumes on the freeway and parallel arterials, vehicle occupancies, truck percentages, transit ridership, congestion data, delay data, travel time data, and accident and incident data.
   - Information from *corridor studies* currently underway or recently completed to compile a list of projects and strategies that have been planned or programmed.
   - A *field review* of each travel mode within the study corridor.

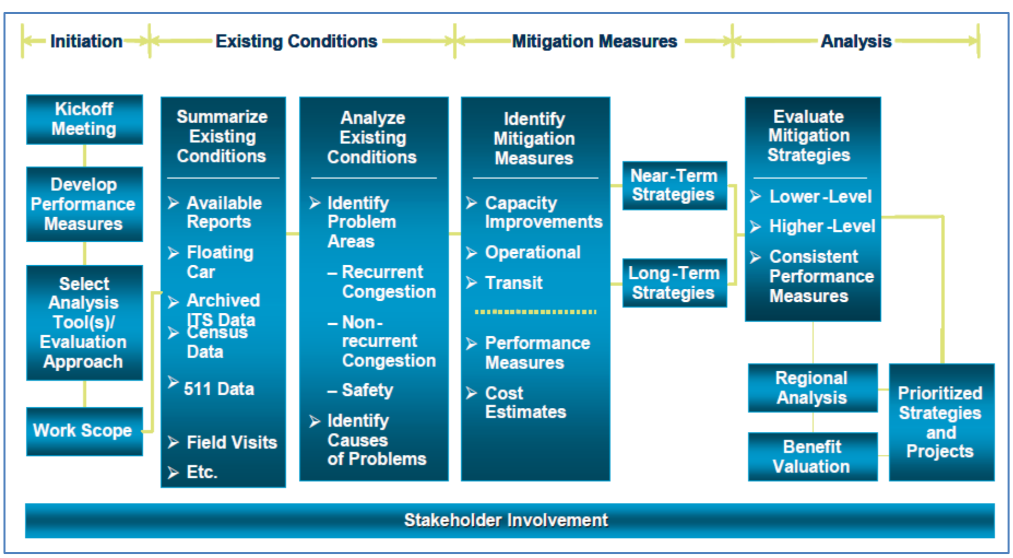

Figure 72 – ICM Evaluation Strategy

3. **Develop ICM strategies and projects** – In this step, the ICM strategies developed for each corridor were to be refined and segregated into short- and long-term implementation timelines, consistent with the Concept of Operations for the site developed in an earlier phase. For each identified mitigation strategy, performance measures were also to be developed.
4. **Evaluation of congestion mitigation strategies and projects** – This step focused on the evaluation of the identified ICM strategies according to the analysis, modeling and simulation framework described in Section 7.3. This analysis was to identify the locations of freeway bottlenecks, changes in aggregate congestion levels in the corridor, and changes in peak-period travel times and delays.
5. **Project recommendation** – A prioritized list of recommended measures and rationale for the prioritization was finally to be developed based on the results of the analysis

7.3. SIMULATION MODELING APPROACH

Figure 73 illustrates the simulation analysis framework that was proposed for evaluating ICM strategies. This framework relies on the combined use of the following simulation tools:

- **Macroscopic regional travel demand models**, for the determination of overall trips patterns within the study area.
- **Mesoscopic simulation tools,** for analyzing the impacts of driver behavior in response to ICM strategies, both within and across models.
- **Microscopic traffic simulation tools**, to evaluate the impacts of traffic control strategies at intersections and freeway interchanges.

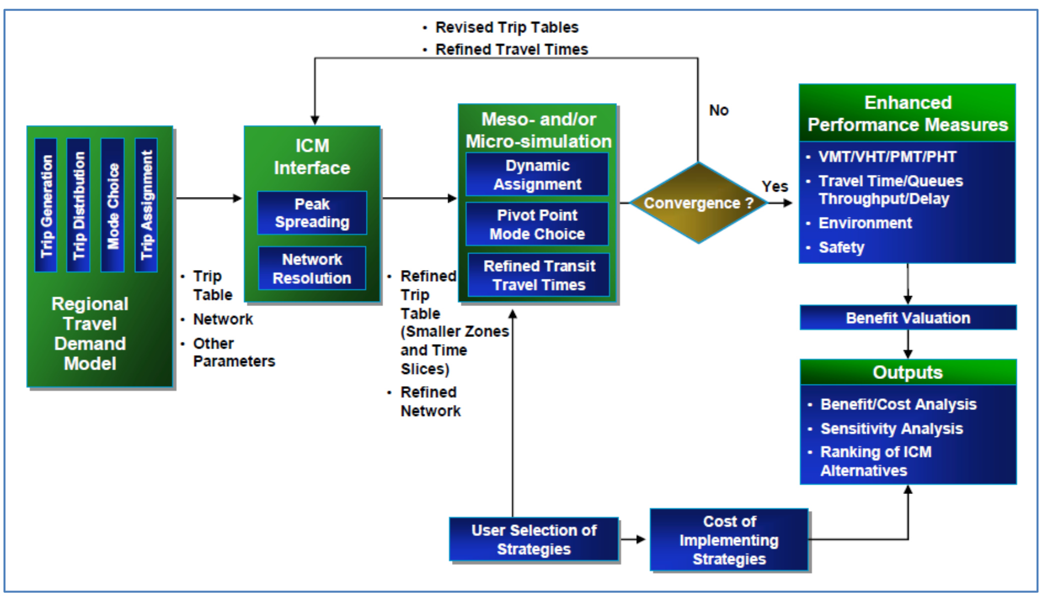

Figure 73 – Framework for the Evaluation of ICM Strategies

The proposed methodology also includes the development of a simple pivot-point mode shift model and a transit travel time estimation module to address known gaps in the analysis of impacts on transit services integrated in a multi-modal corridor. The evaluations required transit travel times at key decision points to be calculated on a segment-by-segment basis within each corridor to support comparisons of network and modal alternatives and facilitate the analysis of traveler shifts among different modes. At the time of the evaluations, very few commercial mesoscopic and microscopic models were found capable of fully representing transit networks, estimating transit travel times, and dynamically adjusting transit travel times on road segments and different decision points. While demand forecasting models could represent transit networks, they were on the other hand deemed not effective at estimating accurate transit travel times, both statically and dynamically.

Within the framework, macroscopic, mesoscopic, and microscopic tools were expected to interface with each other, passing trip tables and travel times back and forth until convergence is achieved. Following convergence, performance measures, benefits, and costs were to be calculated. For each scenario/alternative, benefits would then be compared to deployment costs using benefit-cost ratios. The resulting ratios would in turn be used to rank alternatives and to produce a roadmap outlining an implementation timeline of the proposed ICM strategies.

7.4. ICM SIMULATION MODELING TEST: I-880 CORRIDOR

Prior to the selection of formal evaluation corridors, Cambridge Systematics used a test corridor to assess the application of the analysis, modeling and simulation process described in Sections 7.2 and 7.3 (Alexiadis 2008a, 2008b, 2008c). Following a review of corridors for which either partial or full simulation models already existed, a 34-mile section of I-880 in Oakland, California, extending from the I-580/I-80 interchange in the north to the SR-237 freeway in the south, was retained. This corridor was selected based on the fact it that travel demand, mesoscopic and microscopic models were already available, the existence of validation and calibration data from previous studies, its multi-modal nature, and the presence of a wide array of transportation facilities within its boundaries.

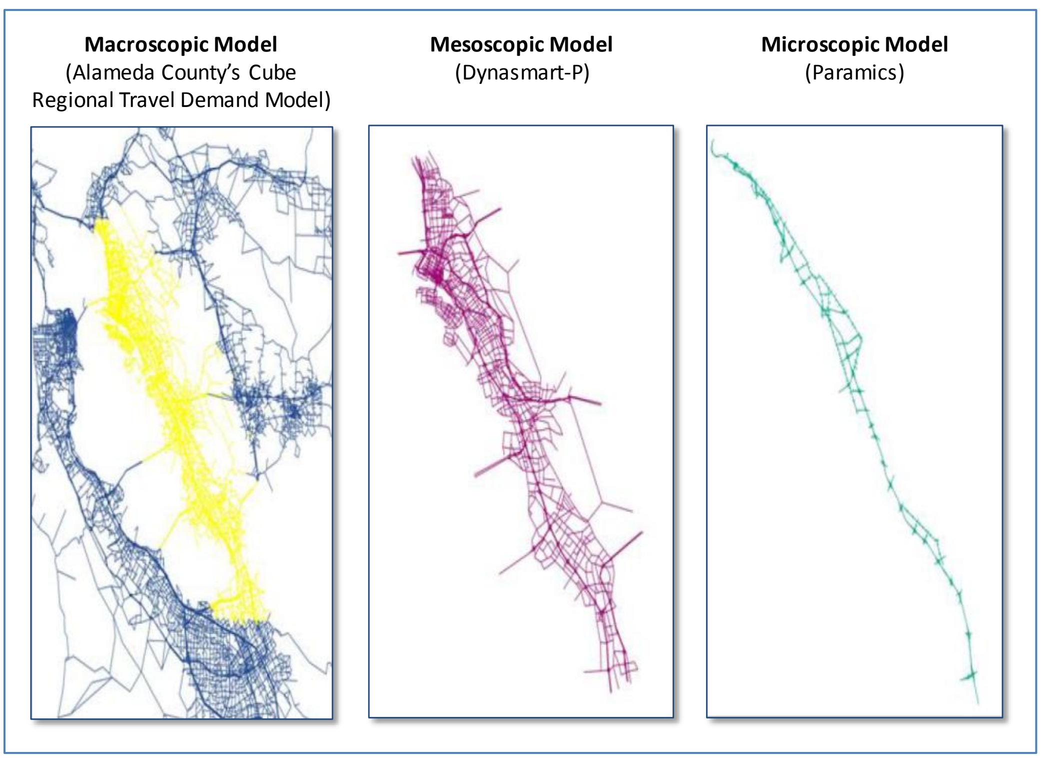

Figure 74 – Macroscopic, Mesoscopic and Microscopic Models of I-880 Test Corridor

Figure 74 illustrates the macroscopic, mesoscopic and microscopic models that were used for the test evaluation. A validated CUBE travel demand model that had been developed by the Alameda County Congestion Management Agency (ACCMA) was retained to develop the trip tables for the test corridor. Both the mesoscopic Dynasmart-P model and a custom-built pivot point analysis model were then used to analyze the dynamic impacts of ICM strategies on travel behavior, such as new pricing strategies and enhanced dissemination of traveler information. While it was initially planned to use a Paramics microscopic model that was under development for the corridor's CSMP operational evaluations, the development schedule of this model did not allow for its use in the ICM evaluation. Had this model been available, it would have been used to evaluate ramp metering and traffic signal coordination strategies. The Synchro/SimTraffic software was instead used to evaluate the impacts associated with traffic signal coordination strategies along the corridor's arterials.

7.5. MODELING OF DEMONSTRATION CORRIDORS

Out of the eight corridors listed in Table 38, three corridors were formally selected to be part of the analysis, modeling and simulation phase of the ICM program:

- **I-15 corridor in San Diego, California** – 21-mile stretch of I-15 north of San Diego. The corridor to be modeled included the I-15 general purpose lanes, managed and HOT lanes along the freeway, frontage roads, regional arterials parallel to the freeway with their primary freeway connectors, park-and-ride lots, and a proposed Bus Rapid Transit system.
- **US-75 corridor in Dallas, Texas** – 28-mile stretch of the US-75 freeway linking Dallas with the city's northeast suburbs. The corridor to be modeled included the freeway mainline, frontage roads, HOV lanes, toll facilities, 167 miles of major regional arterials with approximately 900 traffic signals, two light-rail lines, transit bus service, park-and-ride lots, bike trails, and various Intelligent Transportation Systems (ITS) elements.
- **I-394 corridor in Minneapolis, Minnesota** – 25-mile section of I-314, extending from Minneapolis central business district to the Hennepin County line to the west. The corridor to be modeled included the I-394 general purpose lanes, HOT lanes, freeway frontage roads, two primary arterials parallel to the freeway (TH-55 and TH TH-7) with half-mile signal spacing, several key arterials operating as feeders to the freeway, express and local bus services, several park-and-ride lots, and garages located at the western edge of the central business district.

The evaluation teams responsible for each ICM site were left with the decision to determine which simulation software to use to model their respective corridor. Table 40 lists the models that were eventually retained. In accordance to the modeling approach described in Section 7.3, the modeling of each corridor relied on the utilization of macroscopic, mesoscopic and microscopic simulation models.

Table 40 – Simulation Software Used in ICM Evaluation Projects

Model Type	Regional Travel Demand Model (Macroscopic)	Dynamic Traffic Assignment Model (Mesoscopic)	Traffic Simulator (Microscopic)
US-75 (Dallas)	TransCAD	Dynasmart-P, Direct	VISSIM
I-15 (San Diego)	TransCAD	TransModeler	TransModeler
I-394 (Minneapolis)	TP+	DynusT, Dynasmart-P	CORSIM, AIMSUN

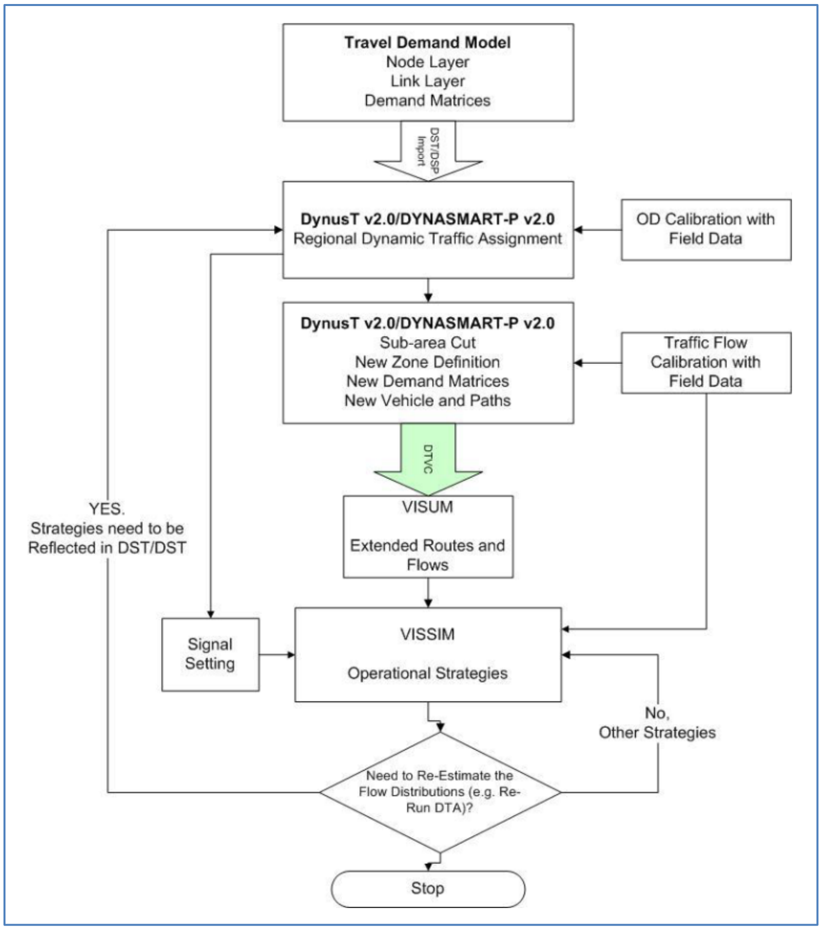

Figure 75 – Simulation Framework Example: I-394 Corridor

To illustrate how the various models were used to model a corridor, Figure 75 presents the simulation framework that was implemented for the I-394 corridor. The figure illustrates an iterative process that was designed to enable equilibrium in traffic flow patterns to be reached. Within the process, initial trip tables were obtained from the regional TP+ travel demand mode. These trip tables were then used to perform dynamic traffic assignments using either Dynasmart-P or DynusT. VISSIM's travel demand model, VISUM, was also used to support the transfer of travel data into the VISSIM microscopic traffic simulator. Based on the results of the VISSIM simulations, a determination was then made on whether the simulated flow patterns could be deemed representative of reality or whether a new modeling iteration was necessary.

7.6. GEOGRAPHICAL SCOPE OF ICM SIMULATION MODELING

Since the objectives of the ICM program are to evaluate integrated corridor operation strategies, the simulation modeling of the various ICM corridors typically attempted to include arterials parallel to the freeways of interest. As an example, Figure 76 shows the extent of the simulation modeling of the I-15 corridor in San Diego. Diagrams of the simulation modeling to be used for the evaluation of the US-75 corridor in Dallas and I-394 corridor could not readily be obtained from a literature search.

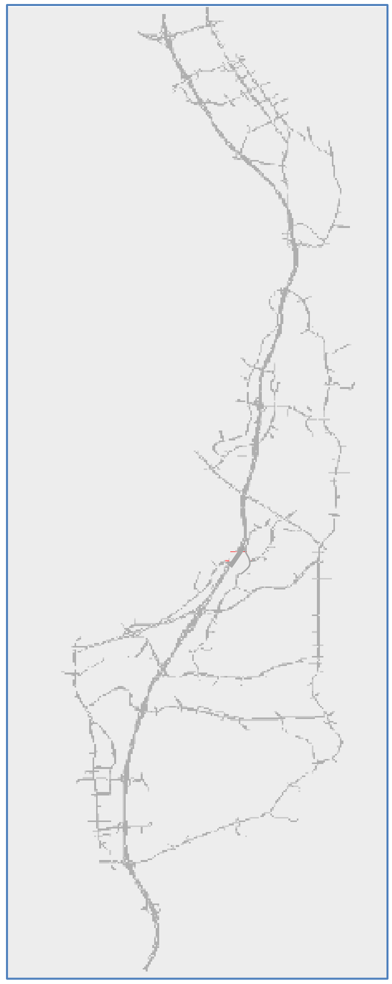

Figure 76 –TransModeler Model of I-15 Corridor

7.7. MODEL CALIBRATION AND VALIDATION

The following outlines the calibration approach that was specifically used for the validation and calibration of I-15 simulation model. While some steps were performed simultaneously, others were performed iteratively until the best results were achieved.

- The first step involved importing the roadway network from the regional macroscopic travel demand model into TransModeler, and performing a geometry check to ensure the correctness of lane configurations and traffic signal locations.
- In the second step, the O-D trip table for the 6:00 – 9:00 AM peak period was extracted from the regional travel demand model and expanded to reflect the desired 6:00-11:00 AM evaluation period. The adequacy of the resulting model was then evaluated by compiling various performance measures under typical 2003 baseline conditions. Known incidents" scenarios were also used to test the sensitivity of the model to major incidents along southbound I-15.

The formal model calibration strategy was based on the three-step strategy recommended in the FHWA guidelines for applying traffic simulation modeling software provided in *Traffic Analysis Toolbox Volume III: Guidelines for Applying Microsimulation Models* (Dowling *et al.*, 2004):

- **Capacity calibration** – An initial calibration was performed to identify values for the capacity adjustment parameters that would cause the model to best reproduce observed traffic capacities. A global calibration was performed first, followed by link-specific fine-tuning.
- **Route choice calibration** – A second calibration process was performed to adjust route choice parameters, starting again with an adjustment of global parameters followed by an adjustment of link-specific parameters.
- **System performance calibration** – Finally, overall estimates of system performance, such as travel times and queue lengths, were compared to field measurements to assess the overall adequacy of the simulation model.

Table 41 – General Calibration Criteria for ICM Corridors

Measure	Calibration Criteria	Acceptance Target
Modeled vs. observed link flows	**Individual link flows:** • Within 15% for links with peak-period flow > 2000 vph **Sum of all link flows:** • Within 5%	> 85% of cases For all link counts
Modeled vs. observed travel Times	**Journey times within network:** • Within 15% of observed travel times	> 85% of cases
Visual Audits	**Individual link speeds:** • Visually acceptable speed-flow relationships **Bottlenecks:** • Visually acceptable queuing	To analyst's satisfaction To analyst's satisfaction

Table 41 lists the calibration targets that were considered for the various corridors (Alexiadis, 2011a). These criteria essentially try to bring the difference between observed and simulated link flows and travel times, within a certain threshold. Visual audits are also conducted to ensure that bottlenecks occur at the right time and place and have the proper impacts on traffic. The targets are similar in concept to the targets recommended by the FHWA that were described previously in Table 15 in Section 3.6. The main differences include the absence of criteria calculating GEH statistics, and the use of a 15% link flow comparison threshold only for links carrying more than 2000 vph during the peak period.

Because two corridors had significant transit presence, additional validation and calibration criteria were established for the modeling of the required transit components. As an example, Table 42 lists the criteria that were applied to the modeling of the US-75 corridor. Due to the importance of considering scenarios involving incidents, calibration criteria were also established for the modeling traffic conditions during an incident, as shown in Table 43

Table 42 – ICM Calibration Criteria for US-75 Corridor Transit Operations

Measure	Calibration Criteria	Acceptance Target
Light-rail station volumes	**Individual station volumes:** • Volumes within 20% of observed values	> 85% of cases
Park-and-ride activities	**Individual parking lots:** • Parked cars within 30% of observed values **Sum of all parking lots:** • Total parked cars within 20% of observed values	All lots All lots

Table 43 – ICM Calibration Criteria for the Modeling of Incident Scenarios

Measure	Criteria
Freeway bottleneck Location	• Should be on a modeled segment that is consistent in location, design and attributes of the representative roadway section.
Duration of incident-related congestion	• Duration observable within 25%.
Extent of queue propagation	• Within 20% of observed queues.
Diversion flows	• Increase in ramp volumes where diversion is expected to take place.
Arterial flow breakdown	• Existence of lack of traffic signal cycle failures

7.8. SCENARIO DEVELOPMENT

Across all ICM sites, evaluations were made by considering network operations under various scenarios. Table 44 lists the specific scenarios that were considered for each corridor. These scenarios were developed by considering various combinations of traffic management strategies, traffic-impacting incidents and traffic demand levels (low, medium or high demand). Traffic conditions were also evaluated for both a base year, typically between 2003 and 2008 depending on the corridor, and a target future year (Alexiadis, 2011a, 2011b).

Table 44 – Scenarios Considered for Stage 2 ICM Evaluation Sites

Types of incidents considered	I-15	US-75	I-394
No incident	●	●	
Major freeway incident	●	●	●
Minor freeway incident		●	●
Major arterial incident	●		●
Minor arterial incident			●
Transit incident	●		
Snow event/Inclement weather			
Ball game/special event	●		
High traffic demand		●	●
Medium traffic demand	●	●	●
Evacuation event / Disaster response	●		

7.9. PERFORMANCE MEASURES

A consistent set of performance measures was developed by the FHWA to assess the impacts of ICM strategies across all evaluation sites. Performance measures were selected to:

- Provide an understanding of traffic conditions in the study area;
- Demonstrate the ability of ICM strategies to improve corridor mobility, throughput, and reliability based on current and future conditions; and
- Help prioritize individual investments or investment packages within the Test Corridor for short- and long-term implementation.

Table 45 – Performance Measures for Stage 2 ICM Simulation Evaluations

Category	Performance Measure
Network mobility	• Travel time • Delay • Vehicle throughput • Person throughput • Capacity utilization (percentage capacity utilized) • Level-of-service (LOS)
Travel reliability	• Change in standard deviation of travel time • Change in Planning Index
Environmental impacts	• Change in fuel consumption • Change in vehicle emissions
Transit operations	• Transit vehicle ridership • Transit vehicle capacity utilization • Percentage of buses arriving late
Costs	• Planning-level costs to deploy, operate and maintain system components • Monetization of benefits using time valuation parameters.
Safety	• Not evaluated
Travel demand impacts	• Percent mode shift • Impacts of incidents on route choice

Table 45 lists the various performance measures that were considered for the evaluations. The primary performance measures that were retained generally attempted to capture aspects of mobility and reliability, as well as environmental impacts. Additional measures assessing the impacts of operational strategies on transit operations and traveler behavior were also considered for evaluations for which such an assessment was deemed important.

The estimation of fuel consumption and pollutant emissions was performed using the ITS Deployment Analysis System (IDAS) that had been developed by Cambridge Systematics under the technical guidance of a steering committee comprised of representatives from a variety of Metropolitan Planning Organizations (http://idas.camsys.com). This system relies on reference values extracted from various available sources, such as the California Air Resources Board's EMFAC 2007 and EPA's MOBILE6 models, to identify the fuel consumption and emissions rates of vehicles on a given facility in a specific situation. Fuel consumption and emission rates are typically estimated based on statistics describing the roadway type, vehicle mix, total number of vehicle-miles traveled and average speed of vehicles. To support the benefit/cost analyses, the resulting emissions and fuel consumption were further monetized using fuel purchase prices and prevailing costs per ton of pollutants released.

While safety performance measures were initially sought, it was realized that available safety analysis methodologies were not sufficiently sensitive to assess ICM strategies. The best available methodologies at the time relied on crude operational measures, such as volume-to-capacity (V/C) ratios, and could not take into account the effects proposed operational strategies on smoothing traffic flows. As a result, safety measures were not included in the final evaluations.

7.10. LESSONS LEARNED

The following are lessons that were learned on the use of simulation to evaluate and manage transportation corridors (Alexiadis, 2008c; Poe, Olyai, and Abdelehany, 2009):

- **Modeling approach** – At the time of the study, there was no simulation tool capable of evaluating across transportation modes and facilities the impacts of all the ICM strategies that were considered. Achieving such an evaluation capability required the utilized of macroscopic, mesoscopic, and microscopic models in an integrated evaluation framework. In developing a suitable integration, the level of emphasis between the macroscopic, mesoscopic and microscopic models further depended on the scope of the project, its complexity, and the questions to be answered.

- **Modeling of traveler information systems** – At the time of the evaluations, there was no clear understanding of the effects of the quality of traveler information on decisions made by travelers or how the disseminated information may influence mode shifts. This situation made challenging the modeling of operational strategies based on travelers responding to disseminated information. A possible approach that was proposed to improve the modeling of such strategies could be to assign different levels of accessibility to information for different groups of travelers. It was also suggested to conduct sensitivity analyses on simulation results.

- **Modeling of mode choices** – Most available simulation models were found ineffective at estimating the potential impacts of operational strategies on mode choice. Travel demand models did represent transit, but were found ineffective at estimating accurate transit travel times. On the other hand, very few simulation models could fully model a transit network, and none could dynamically adjust mode choices in real-time. This was deemed important as short-term mode shifts may be very different from long-term shifts. A solution to this issue was to use a simple pivot-point mode choice model that could work with trip tables from travel demand models, and to work with travel time estimates from traffic simulation models, and to use a simple geographic information system (GIS) representation of transit networks.

- **Modeling of congestion** – 15-minute traffic counts were found to be not particularly beneficial for the calibration of traffic demand since the observed counts could reflect a capacity constraint, and thus, not the actual demand. In this case, speed-density relationships developed from observed flow data were found useful to help model congested conditions.

- **Data quality and reliability** – Reliable data are essential to the development of dependable simulation models, the comparison of strategies, and development of a complete operational picture of the transportation system. However, the modeling efforts revealed that obtaining consistent data for arterials, transit, and incidents can often be a challenge.

- **Data collection** – Gathering necessary input data presents multiple challenges, such as knowing where to place detectors, having a way to determine when sensors are down, ascertaining corridor behavior between detectors, and deciding when to accept or reject field data. To ensure reliability, agencies need to replace defective sensors quickly and be able to change installation and testing standards for their data collection equipment. On this topic, it was felt that more work was still needed to determine optimal detection layouts for monitoring and identifying traffic patterns within a transportation system.

- **Data filtering and fusion** – There is a clear need for standards on accepting or rejecting field data, as well as addressing data gaps and missing data. Another identified need is to explore methods to combine or fuse data from different sources or technologies. Experiences from the project further indicate that changes in maintenance practices may be required to enable the quick replacement of defective data collection equipment, particularly equipment that would provide data critical to the modeling effort. Finally, a need to develop or refined installation and testing standards for sensor equipment was also identified.

- **Model calibration** – Various reasons can explain observed deviations between simulation model estimates and typical day performance:
    - The data samples used for calibrating the simulation model may not include the full range of day-to-day variations in traffic demand or traffic conditions.
    - Not all travelers perceive congestion the same way, resulting in different persons responding differently to congestion.
    - Trip tables from travel demand models may be based on data that has been collected at different times than the typically day used for the simulation modeling, or data that may have been aggregated too coarsely.
    - The temporal resolution of trip demand tables may not be refined enough to accurately match observed travel patterns during a typical day.
    - The aggregation/disaggregation of zones at the corridor network boundary may produce inconsistencies with larger travel demand models.

- **Model validation** – The criteria and data that will be used to validate a simulation model must be defined early in a modeling project.

- **Development of evaluation scenarios** – The traditional analysis approach of considering a “typical day” is not very useful when evaluating corridors with significant variability in traffic conditions. In such cases, focusing the analysis on different operational scenarios is more useful. As an example, 25 percent of the days in one case study had both major incidents and high demand, while 22 percent of all days featured both low demand and minor incident conditions. Since approximately 40 percent of the total annual delay along the study corridor occurred on the worst 25 percent of the days, targeting strategies to address days with high incident and high demand resulted in significant benefits. Because one type of analysis does not necessarily fit all conditions, a need was thus identified to focus on different operational conditions. Scenarios that should be examined include days without incidents, with incidents, with different weather conditions, with high travel demand, and with special events.

- **Evaluation of multi-modal networks** – A need was identified to determine methods for comparing and measuring multi-modal information.

- **Usefulness of simulation models** – It is important to remember why a simulation analysis is performed. Typically, it is to help invest in the effective strategies to improve corridor performance. In this context, simulation models provide a valuable predictive capability to help determine which combinations of strategies are the most effective. Another objective is to help decision-makers to make sound investment decisions and minimize the potential for conflicts or unintended consequences resulting from a lack of adequate knowledge about the potential impacts of proposed operational strategies. Results from simulation models can, for instance, improve the effectiveness and success of proposed implementations by helping stakeholders to build consensus on the desirability of a specific strategy and by subsequently helping determining when individual strategies can best be deployed.

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8. GAPS AND CRITICAL ISSUES

This section presents gaps and critical issues that have been identified on the use of simulation models in support of corridor operational evaluations. The gaps and issues presented herein are organized around the following categories:

1. Role of simulation as evaluation tool;
2. Selection of modeling tools;
3. Simulation modeling capabilities;
4. Resources needed;
5. Data collection, preparation and validation;
6. Geographical scope of modeling;
7. Demand modeling;
8. Model calibration and validation;
9. Scenario development;
10. Model review process;
11. Model application;
12. Performance measures considered;
13. Prioritization of evaluated improvements;
14. Data presentation;
15. Documentation of modeling and simulation efforts; and
16. Model maintenance.

8.1. ROLE OF SIMULATION AS A CORRIDOR EVALUATION TOOL

There is still much debate within Caltrans on the role of simulation as a tool for the evaluation and ranking of corridor improvement alternatives. The debate generally stems from the significant time and costs that have been required for the development of microscopic models supporting CSMP operational evaluations. The extent of the resources that have been required has naturally brought some individuals to question the efficiency of using traffic simulators, particularly microscopic models with data-demanding needs, for evaluating long or complex corridors. On the other hand, there are other individuals who recognize and value the contributions that microscopic simulation models can make to corridor evaluations.

While microscopic simulation tools have been available for more than 20 years, early modeling capabilities were significantly more restricted than they are now. Capabilities for visualizing road networks on-screen were also very limited. As a result of these limitations, corridor evaluations largely relied on the use of analytical tools and, to some extent, macroscopic simulation models. Over time, many new features have greatly expanded the modeling capability of microscopic simulators and simplified the network coding tasks. However, despite these improvements, the large quantity of input data required and more complex calibration have continued to restrain many individuals from embracing the use of microscopic simulation models to support corridor operational evaluations.

To a certain extent, the current CSMP modeling efforts have demonstrated that it is possible to use microscopic simulation models to support the evaluation of long and complex corridors. While significant resources were indeed dedicated to the modeling efforts, modelers and project managers have gained with each new evaluation additional experience, knowledge and expertise on how to manage large microscopic simulation projects. These gains can be expected translate into further saving in modeling time and budget with future projects. The recent completion of the I-5 corridor CSMP in Orange County in only 12 months and for significantly fewer resources than previous microscopic evaluations is a good testimony to this trend.

Another area of concern is not directly related to the technical capabilities of individual models but to the expectations that are placed on these models by decision-makers. While the use of simulation to support corridor operational evaluations is relatively recent, some individuals have already expressed concerns that decision-makers may put too much faith on the capability of existing tools, whether macroscopic, microscopic or mesoscopic models. It should not be forgotten that simulation models are mathematical abstractions of the reality. They cannot be expected to fully replicate the complexity of human driving behavior in every situation. Simulation results should only be viewed as estimates of real-world behavior reflecting the many assumptions supporting the simulation models. There is thus still a need to educate decision-makers on simulation model capabilities and to ensure that appropriate expectations are placed on the potential roles of simulation models in corridor evaluations.

8.2. SELECTION OF MODELING TOOLS

The following are issues that should be considered regarding the selection of which type of simulation tool to use to conduct a corridor evaluation:

- **Microscopic or macroscopic modeling** – Macroscopic tools offer fast execution speeds due to their simplified modeling. Instead of modeling individual vehicles, they assess traffic behavior by considering relationships between flow rate, traffic speed, and flow density. While the use of macroscopic tools has significantly declined in the past 10 years, largely to the benefit of microscopic tools, they can still be used to assess improvements where the primary effects can be expressed in flow rates, density and/or average speed. As an example, macroscopic models can still be used to evaluate ramp metering strategies where the metering rate is based on average flow characteristics, but not systems using dynamic rates based on individual spacing between vehicles. They can also be used to evaluate auxiliary lane additions or geometrical ramp improvements if it is assumed that these changes will not affect general traffic behavior (for instance, that changes will not reduce or increase the frictions caused by lane changes).
- **Microscopic or mesoscopic modeling** – Recently, significant attention has been devoted to the ability of mesoscopic models to simulate large networks at quicker speeds than microscopic models. Their ability to handle large networks has notably resulted in their frequent use in academic circles for solving dynamic traffic assignment problems. However, their use may not be without a certain loss of accuracy when compared to microscopic models as a result of their reliance on simplified driver behavior models. The jury is thus still out on the ability of using these models for corridor operational evaluations.
- **Suitability of hybrid modeling approach** – Some simulation tools now allow for the development of road networks modeling certain areas using microscopic principles and others using mesoscopic principles. While there were three attempts to model CSMP corridors using such an approach, calibration difficulties eventually led two modeling teams to switch back to a microscopic-only approach. While one hybrid model was completed, there are still concerns regarding its accuracy. These negative outcomes are not necessarily an indication that hybrid approaches are not viable. Since the CSMP modeling efforts were among the first attempts at modeling large corridors using an hybrid approach and involved using newly released features

within the TransModeler model, it is possible that model refinements implemented since then may have resolved some of the problems that were encountered.

- **Availability of required data** – Simulation models, and more particularly microscopic models, require a significant quantity of data to appropriately set up and calibrate model parameters. Without good data upon which to build the model it is unlikely that a model will provide meaningful results. While a lack of data may entice the selection of a simpler model (e.g., macroscopic model), such a decision can limit the types of operational strategies that may evaluated. Depending on the situation, it may still be best to try to collect the missing data rather than seek a simpler model, if adequate resources are available to support such a task.
- **Computer run time** – An argument often invoked in favor of mesoscopic or macroscopic models is quicker execution speed. Mesoscopic models typically run faster than microscopic models, while macroscopic models in turn run much faster than mesoscopic models. While quicker models allow evaluating more scenarios or executing more replications for each scenario, execution speed should not be a dominant factor in the selection of a simulation tool. Many microscopic models now offer the capability to program batch simulation sets that can be run automatically. Some models also allow distributed processing, in which a set of simulations is distributed to a series of networked computers. Concerns about run times can also be partly mitigated through the use of more powerful computers.
- **Ability to model improvement strategies of interest** – Agency staff should refrain from using a model that may restrict their ability to evaluate key improvement strategies. While it can be attractive to continue using a model that has been used with satisfaction in the past, it is more important to select tools that can adequately represent the improvement strategies that are currently of interest. Developers of commercial simulation software closely follow application trends and periodically integrate new modeling capabilities within the tools they offer. The use of older models that are no longer being developed, such as FREQ 12 or CORSIM, may restrict evaluations to past standard practices and prevent consideration of new promising strategies.
- **Availability of third-party expansion plug-ins** – Various consulting firms have relied on the application programming interfaces (APIs) offered by commercial simulation tools to develop plug-in packages expanding the modeling capabilities of these tools. Examples include modules replicating ramp metering algorithms or implementing enhanced driver behavior around HOV lanes. Many of these plug-in modules can be obtained from their developer either for free or for a modest licensing fee. Prior to selecting a simulation tool, it would therefore be a good practice to assess not only the tool's built-in capabilities but also the potential for obtaining third-party plug-in modules implementing desired functionalities.
- **Ability to develop plug-ins using Application Programming Interfaces (APIs)** – In addition to the ability to acquire third-party plug-ins, teams interested in evaluating emerging applications should explore the capability of developing in-house expansion modules with each of the candidate simulation tools. Developing plug-ins in-house would require staff familiarity with the modeling principles of the simulation tool, as well as the programming language required to develop the modules. While the development may be contracted to an external consultant, this option would still require an ability to review the developed modules for accuracy.
- **Agency expertise with simulation tool** – While consulting firms often have expertise in a wide variety of simulation tools, Caltrans staff within District offices appear to have expertise in a narrower range of simulation tools. To facilitate the review process and potential future uses of a developed simulation model, the selected simulation tool should ideally be one in which

Caltrans district staff already has some expertise. However, as outlined earlier, this criterion should not be used to arbitrarily exclude the use of alternate models offering better modeling capabilities for the improvement strategies considered.

- **Training needs** – Selection of a new simulation tool will require training some individuals in how to use the model. This not only applies to modelers and technicians, but also to individuals who may be asked to review the modeling efforts conducted with the model.
- **Ability to migrate software version** – Traffic simulation software developers periodically release new versions of the tools they offer to introduce new features and fix software bugs. Software releases with changes to the underlying behavioral models will typically cause networks developed with earlier versions to produce different results. Consequently, older road networks will often require re-calibration when ported to a new version. Agencies should therefore account for the difficulty or ease with which these periodic recalibrations can be accomplished when selecting a simulation tool.
- **Diverging jurisdictional preferences** – Agency's individual preferences often factor into the selection of a simulation tool. This can result in diverging modeling preferences for projects crossing jurisdictional boundaries or incorporating transportation elements operated by different agencies. In such cases, it is important to develop a consensus based on mutual needs to determine what would be the preferred simulation tool.

Additional guidance on the selection of an appropriate simulation tool can be found in *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools*. (Jeannotte *et al.*, 2004). The document identifies several criteria that should be considered and helps identify the circumstances when a particular type of tool should be used. Assistance is also provided to guide users in selecting an appropriate tool category and in identifying the most appropriate tool within a category.

8.3. MODELING CAPABILITIES

The following items are issues that have been identified regarding the modeling capabilities offered by existing simulation tools:

- **Unrealistic expectations –** Individuals who do not regularly use simulation tools often have unrealistic expectations regarding their capabilities due to a lack of understanding of the various elements that can affect simulation results, particularly when simulating congested networks. If not addressed, these unrealistic expectations can lead to the perception that using simulation model can be a waste of resources following disappointing experiences. It is thus important that project managers and decision-makers be adequately informed of the limitations and risks associated with the use of simulation tools.
- **Size of network that can be modeled –** While many simulation tools impose an upper limit on the number of nodes and links that can be coded, these limits are generally well beyond the needs of typical CSMP corridors, particularly if using professional-level software licenses. In most cases, the processing capabilities of the computers on which the simulation tool is installed will determine the maximum size or complexity of a network that can be developed. While there may be no software limitation, the modeling of large networks should not be necessarily favored, as larger models typically require more data to be collected and are often more difficult to calibrate. The size of the network to be modeled should reflect the objective of the evaluations and available resources.

- **Ability to reliably evaluate long-term improvement projects** – Simulation models can be effectively used to evaluate projects scheduled to be implemented in the near term. However, difficulties often arise when attempting to evaluate improvements that may not be in place for another 20 or 30 years. A problem that is often encountered is the inability of the coded road networks to handle the projected traffic growth. While an option may be to evaluate the desired improvements at a nearer horizon, such an evaluation would not allow the full magnitude of the benefits that may be realized in 20 or 30 years to be quantified.
- **Modeling of ramp metering systems** – While ramp metering is frequently used in California, most existing simulation tools only offer simple built-in capabilities for modeling metering systems. In most cases, fixed metering rates can be modeled using available signal timing functions. For the CSMP modeling efforts using Paramics, VISSIM and TransModeler, the modeling of the ALINEA, Semi-Actuated Traffic Metering (SATM) and San Diego Ramp Metering (SDRM) metering systems further benefited from the availability of software-specific plug-in modules that had been previously developed. However, modeling efforts seeking to evaluate new metering algorithms will almost certainly require the development of new plug-ins, either by the modeling team itself or through a subcontract with an external developer.
- **Modeling of advanced or custom traffic signal operations –** State-of-the-art microscopic and mesoscopic tools generally have built-in capabilities for the coding of standard fixed-time and actuated traffic signal operations. However, these capabilities may allow the modeling of more advanced or custom signal control systems. While some systems may be suitably approximated using available signal control functionalities, these functionalities can be insufficient in other cases, thus requiring the development of custom plug-in modules. Since plug-in development can be a complex endeavor, an assessment should be made to determine if accurately replicating the traffic signal control system in question is crucial for the evaluations.
- **Modeling of managed lane systems** – Many simulation tools now allow the modeling of HOV lanes, as well as HOT lanes with fixed pricing and variable pricing based on congestion. Relatively simple techniques have also been proposed to model reversible lanes. However, refinements to driver behavioral models are still required to allow adequate replication of traffic behavior around HOV/HOT lane entry and exit points. Finally, while commonly used systems can generally be modeled using built-in functionalities, the evaluation of innovative management strategies will generally require the development of custom plug-in modules or utilization of modules developed by third-parties to expand the functionalities of the simulation tool being used.
- **Modeling of transit applications** – Many commercial simulation models now allow the modeling of scheduled-based transit services and the simulation of boarding and alighting activities at bus stops. However, the models remain generally incapable of simulating changes in mode choices, such as travelers switching from cars to buses as a result of congestion. This behavioral aspect must still be evaluated using external models.
- **Connected vehicle applications** – While there is a growing interest in applications attempting to leverage emerging wireless communication capability to and from vehicles, simulating such applications still generally requires the development of specialized plug-in modules.

8.4. RESOURCES NEEDED

This section provides an assessment of resources that may be needed for the development and execution of traffic simulation studies. Elements discussed herein cover the following five topics:

- Time and budget allocations;
- Staffing needs;
- Professional capability;
- Computer hardware; and
- Supporting software.

8.4.1. TIME AND BUDGET ALLOCATIONS

Adequate time and budget must be allocated to a modeling project. While this requirement appears self-evident, a number of persons who were contacted as part of this project indicated that time and budget constraints have affected modeling tasks. In some cases, the constraints were the results of unrealistic expectations from consultants regarding what would be needed to develop and calibrate a large traffic simulation model. In other cases, they were the results of decisions altering the scope of a project after it had been initiated. These examples indicate a need to consider the potential impacts on timeline and expenditures of all project decisions.

8.4.2. STAFFING NEEDS

Caltrans currently does not have on staff a core group of individuals specifically tasked with the execution of simulation studies. This leads to a heavy reliance on work performed by external consultants. While this arrangement allows simulation projects to be completed, it does not allow Caltrans to develop an expertise in the use of simulation models that could be used for future projects. Developing a Simulation Unit similar to the current Computer Assisted Design (CAD) unit could help address this situation. Development of the unit could start with one person in each District or in a few key Districts and be gradually expanded. Initial positions may also be filled by simply redirecting existing personnel effort. Over time, the unit would then not only provide Caltrans with the capability to execute simulation studies in-house, likely at a lower cost than using external consultants, but also provide a pool of expertise that could assist in the review of models submitted by external consultants.

8.4.3. PROFESSIONAL CAPABILITY

Developing large simulation networks requires the involvement of individuals with adequate knowledge of traffic simulation principles and of the modeling features offered by the simulation package being used. Knowledge of traffic engineering, design concepts practices and standards are also necessary. While a novice modeler can perform many of the simpler modeling tasks, it is crucial that adequately experienced individuals be tasked with the more complex modeling issues and be put in charge of the overall effort. Adequate expertise is important as many modeling aspects can affect traffic behavior in ways not readily apparent to untrained eyes.

Individuals with programming experience may also be required for modeling efforts that seeking the development of plug-in modules. Individuals having knowledge of the specific programming language used by the simulation tool are more specifically required. This language may be C, C++, Python, or a

GIS scripting language such as GIS-DK. A working knowledge of how to develop Dynamic Link Libraries (DLLs) may further be required. Ideally, programmers should have a working understanding of the traffic simulation principles employed by the simulation tool for which the plug-in is destined. If such individuals are not available within the agency, help from external consultants specializing in the development of plug-ins or the firm responsible for the simulation model development can be sought.

Many Caltrans District offices do not have individuals with the necessary modeling experience to develop and calibrate road networks in the desired simulation tools. Where such individuals are on staff, limited available resources often limit their involvement in modeling activities. To address this issue, many District offices rely on contracts with external consultants specializing in such work to develop simulation models. While this approach requires fewer District staff, it does not necessarily lower modeling costs, particularly if external consultants are routinely used. It also does not eliminate the need to maintain on staff individuals with adequate knowledge of simulation tools to ensure an adequate oversight of modeling activities, particularly during the model review process.

8.4.4. COMPUTING HARDWARE

Computer hardware requirements are not seen as a major impediment to the use of traffic simulation as all existing commercial software can be run using standard off-the-shelf computers. While early models often imposed low limits on the number of nodes and links that could be coded, advances in computer technology have largely pushed this limit beyond the typical needs of current corridor evaluations.

Despite fewer limitations, computer performance may still affect projects. Older computers with slower processors, smaller available memory, and smaller hard drives can run significantly slower than state-of-the-art computers. The difference in execution speed may not significantly affect small modeling projects, but can have a significant impact on large projects or networks featuring high congestion levels. In many cases, performance can be improved by simply purchasing a high-performance computer. Many models also offer a batch processing mode allowing simulations to be run without graphic components, thus at much faster speeds. Some models further offer distributed computing features to allow a series of runs to be executed by an array of computers within an office network.

The number of license seats available is another factor to consider. Most simulation software is purchased with licenses specifying the number of computers on which the model can be run. Some licenses allow installation on any computer and only restrict how many persons can be using the model at a given time. Other licenses require that a dongle be attached to the specific computer from which the model is run, thus limiting the number of users to the number of dongles available. Having an appropriate number of seats is critical, as having too few licenses can limit the how much work can be done in parallel and can lengthen the overall duration of the modeling effort.

8.4.5. SUPPORTING SOFTWARE

Virtually all existing simulation packages exist as stand-alone software and do not require per se the purchase of additional software beyond the simulator itself. However, because of the need to compile and manipulate input data, as well as post-process simulation outputs to extract specific performance measures, the utilization of data analysis tools is often a companion requirement to the use of simulation models. For most projects, data analysis can typically be accomplished using simple spreadsheet tools, such as Microsoft Excel.

8.5. INPUT DATA COLLECTION, PREPARATION AND VALIDATION

Simulation models are only as good as the data that are used to develop them. With models that have been developed using data incorrectly, capturing network geometry or traffic flow behavior will likely produce inaccurate operational assessments. To ensure the reliability of evaluation results, it is therefore important that adequate attention be given to the collection, preparation and validation of input data. Simply collecting and formatting data for use in a simulation model is not sufficient. There should be proper validation of all collected data, regardless of the source, to avoid using erroneous information or significant outliers for the development or calibration of simulation models. Methods to address data coverage problems and discrepancies between alternate sources should also be developed.

Below is a summary of specific problems that were encountered by modeling teams regarding the collection and preparation of input data across the various CSMP corridors:

- **Presence of erroneous data in collected samples** – Due to technical glitches, sensing equipment may on occasion return erroneous data. These errors can be relatively easy to spot, such as an average recorded speed of 90 mph, or difficult to uncover without a detailed data analysis, such as a systematic error that creates a gradually increasing bias in the recorded speeds. It is therefore good practice to always check all collected data for validity. In this matter, it should never be assumed that data that were supplied by monitoring systems featuring a built-in filtering mechanism are necessarily error-free, as some errors may not be the result of faulty equipment but of problems with the communication system used to move the data around.

- **Inconsistencies among data sources** – A number of CSMP modeling teams have reported the need to address inconsistencies within the collected data sets. Some of these inconsistencies were within data provided by a specific system, such as flow data collected by adjacent PeMS stations along a freeway, or between data originating from various sources. These problems often led modeling teams to apply data balancing or other adjustments techniques to resolve or reduce the inconsistencies and ensure that a relatively coherent set of information was used to support the modeling effort.

- **Reliability of estimated data** – Some collected data may not have been directly observed but rather estimated from other pieces of information. An example is the data imputation process that PeMS uses to replace missing data from malfunctioning sensors. This process relies on information collected at neighboring traffic sensors to replace data that may be missing or flagged as corrupted from a given sensor. For this type of data, particular attention should be paid to verifying that the estimated values are valid and reasonable, as errors or biases in the source data could affect the inputted values.

- **Presence of obsolete data in information databases** – Some of the data that may be retrieved from databases may not accurately reflect the existing road geometry or existing system operations. For instance, due to a lag in data maintenance, the information contained in a database describing the traffic signal timing plans in use along an arterial may not reflect the changes that have been made to the plans a few weeks prior to the time when the data was retrieved. To avoid using obsolete data in modeling activities, particular attention should be directed to verifying the time at which each data set is said to have been recorded. Any critical information deemed obsolete should be replaced, adjusted or removed.

- **Data availability outside freeways** – While there is typically a high density of traffic sensors along freeways, large surveillance gaps were often encountered along arterials. These gaps can be due to the absence of traffic sensors between intersections or the inability to automatically retrieve data collected by sensors connected to traffic signal controllers. Such gaps required many modeling teams to evaluate the need to conduct additional field data collections to fill data gaps that were deemed critical to the success of the modeling effort.
- **Missing data** – Data collection efforts occasionally resulted in the inability to collect some desired information. These gaps created a need to develop procedures for estimating realistic values for the missing data using available information.
- **Temporal variability of collected data** – Collected data often included information recorded at different points in time, for instance, data collected on different weekdays or the same weekday in different weeks or months. These temporal differences can be an issue when attempting to fuse data collected over several months or years, as data collected at periods relatively far apart can be representative of different traffic conditions.
- **Data with different aggregation levels** – Data collected from various sources may exhibit different aggregation levels and thus require some processing prior to being merged with other data. For instance, collected traffic flow data may include both 15-minute and 1-hour counts. While aggregating data is often straightforward, disaggregating data can be challenging where it cannot be assumed that the aggregated data can be uniformly distributed over smaller intervals or measurement units.
- **Limited temporal coverage of manually collected data** – Many CSMP modeling efforts used manual data collection activities to supplement the data that could be obtained from continuous monitoring systems. While the additional data was valuable, it often only captured observations over one, two or three days. Collecting data over such a short interval carries the risk that the resulting information may not truly reflect average behavior. For instance, data collection may be tainted by incidents that have occurred along the corridor during the collection period, as well as indirectly by events that have occurred on other corridors. While the above problem can be reduced by collecting data over more days, project resources may not allow for such a solution. Alternatively, verifications can be made to assess that no event along the corridor has affected the collected data during the recording period.
- **Time and budget constraints** – While it is generally recognized that it is preferable to collect data over as many days as possible, time and budget constraints often imposed limits on the quantity of data that could be collected. This forced modeling teams to make careful decisions about what should be and should not be collected to ensure that all data critical to the modeling effort could be collected in sufficient quantity.

In addition to performing the data validation tasks, there should be proper documentation of the data validation activities. The documentation should not only cover the data checks that were conducted but also how the problems that were uncovered were eventually addressed. Such documentation can become useful at a later stage, particularly if it allows for the explanation of problems that are encountered with the development or calibration of a model. This was unfortunately not done consistently across all the CSMP modeling efforts. While many reports list the data that were collected, little information is provided on the data validation checks that were made. There is, however, evidence that some data validation checks were conducted, as some reports detail problems that were encountered with the collected data.

8.6. GEOGRAPHICAL SCOPE OF MODELING

The geographical scope and complexity of a modeling project defines the extent of the road network that is to be modeled. For the CSMP operational evaluations, simulation models covered at a minimum the freeway mainline and ramps. Where not constrained by software limitations, freeway interchanges were also fully modeled. Beyond these elements, the following elements were considered by various teams to define the geographical scope of a corridor:

- **Extent of modeling of intersecting arterials** - While it is often desirable to extend the modeling of intersecting arterials as far as possible upstream from each interchange, doing so significantly impacts project resources. Many of the modeling teams indicated being constrained by time, budget, limited resources and/or limited data. This resulted in a need to strategically select what could realistically be modeled with available resources, which often led to constraining the model's reach beyond the freeway.
- **Extent of modeling of arterials parallel to a freeway** – The modeling of arterials running parallel to a freeway can add significant complexity to a modeling effort. This added complexity not only arises from the need for more data, but also from the need to ensure that the simulation model will adequately route vehicles along freeway and arterial segments. In most cases, this involves adjusting link costs and weights assigned to travel times and travel distances during the model calibration. While the calibration parameters are straightforward, the process for calibrating route choices can be particularly difficult and time-consuming in networks offering a high number of potential alternate route combinations.
- **Possibility of breaking long corridors into smaller sections** – There may be advantages in breaking up long freeway corridors into smaller pieces that can be modeled separately. This can simplify the demand estimation process and model calibration, in addition to reducing modeling and evaluation times by allowing work to be conducted in parallel on each section. However, not all corridors can necessarily be divided. A key aspect is to avoid affecting the evaluation of congestion propagating from bottlenecks, which leads to considering placing break points only on low-volume sections of a corridor. Splitting corridors can also create a need to develop overlapping sections to be included in each sub-corridor.

When developing the geographical scope of a project, it is particularly important to tie the scope of the modeling to realistic expectations. While it may be desirable to extend the modeling significantly beyond the freeway mainline, it should be recognized that a larger modeling area will significantly increase the data collection needs and resources required. The geographical scope of a model should therefore be balanced against the need of a project and available time, budget and resources.

8.7. DEMAND MODELING

Modeling efforts generally relied on data extracted from regional travel demand models or traffic flow counts to develop O-D flow patterns. In most cases, the O-D matrices were developed using algorithms provided by the simulation tool being used or commonly accepted modeling practices. Specific issues that were identified during these activities regarding the estimation of traffic demand patterns include:

- **Need to disaggregate data provided by regional travel demand models** – Data provided by regional travel demand models often characterize trips between zones that are much larger than those defined in the traffic simulation model. These differences often force modelers to estimate how to distribute the trips associated with large zones into a sets of smaller zones. This process notably carries the risk of introducing human errors in the modeling. While techniques to adjust O-D flow matrices based on observed vehicle counts can be used instead to help develop realistic patterns, the initial trip distribution estimates that may have been made by a modeler may still bias the adjustment process and lead to inaccurate flow patterns.

- **Adequacy of one-hour demand pattern intervals** – While a generalized practice was to develop traffic demand patterns for each hour of simulation, using one-hour intervals may be too coarse for conducting operational evaluation on corridors within significant fluctuations in traffic demand. A particular danger lies at the boundary of two time periods, when a sudden change in vehicle release rates can cause an unrealistic surge in simulated traffic and artificial congestion. Only a few efforts developed more refined 15-minute patterns. A few modeling teams went further and took advantage of features offered by the simulation tool being used to modulate vehicle release rates within each hour in 5-minute intervals.
- **Realism of trip patterns produced by origin-destination matrix estimation (ODME) techniques** – The algorithms used to develop O-D flow matrices matching observed traffic counts taken from various locations across a network do not guarantee the replication of actual flow patterns. For instance, link volumes can be matched using different combinations of trips between origin and destination zones. Modelers should therefore always check whether the resulting O-D flow matrices recreate known travel behaviors, such as the right proportions of long, medium and short trips on freeways, and make any required adjustments.
- **Unequal data coverage effects** – While traffic flow counts are commonly used to help develop O-D flow matrices reflecting matching observed link volumes, the estimation process can be influenced by the fact that there are often more data available from freeways than surrounding arterials. Inequalities in data coverage can result in different accuracy levels across a network, even in an inability to accurately reproduce flow patterns in areas with poor detection.
- **Ability to adequately predict corridor operations for horizons far into the future** – Many individuals questioned the merits of developing microscopic models, as well as mesoscopic models, to assess corridor operations 20 or 30 years into the future. Most of these comments were not targeting the modeling capability of individual models, but rather the ability of modelers to develop reliable traffic demand representation for simulation models. While travel demand models can provide valuable insights on potential growth in traffic demands reflecting projected changes in land use and population, it must be understood that these forecasts are based on educated assumptions of what may happen in the future and do therefore carry some uncertainty, particularly for projections made 20 or 30 years into the future. The potential for diversion between predicted and actual network operations will typically increase with the consideration of horizons further into the future. For such evaluations, it is thus often argued that using simpler simulation models, such as macroscopic models, may be a better approach.

8.8. MODEL CALIBRATION AND VALIDATION

Below are critical issues that have been identified regarding model calibration and validation:

- **Error checking** – Adequate error checking prior to model calibration is critical. The critical aspect of error checking arises not only from the potential that coding errors can unduly affect simulated behavior and model parameter values, but also from the fact that individuals tasked with the review of a model may not have the necessary technical expertise to capture all the elements that should be reviewed.

- **Review of default model parameters** – Simulation models typically assign default parameters to various model elements based on observed behavior in their country of origin. This behavior can differ significantly from that within the corridor to be modeled. For this reason, it is usually good practice to assess the relevance of all assigned default parameters and to replace any value thought to be not representative of local conditions. Usually only a few key parameters will require adjustment. Many modeling teams used data that was collected for their corridor to revise certain model parameters. Some teams also invoked prior modeling experience or reports documenting other local projects to justify parameter replacements.
- **Consistency of calibration standards** – While modeling teams generally followed the calibration targets recommended by the FHWA and Caltrans, all teams did not always seek to satisfy the same criteria. Some teams calibrated travel times against end-to-end corridor trips while others considered travel times across individual segments. While most teams compared simulated and observed link volumes, one team did not. Very few teams further evaluated whether turning counts at modeled intersections matched observed traffic behavior.
- **Calibration criteria based on "engineering judgment" or "analyst satisfaction"** – While the ability to replicate observed bottlenecks was a calibration target, this target was only vaguely defined. Modelers and model reviewers were left to their own judgment to assess the quality of the calibration. While such vaguely defined criteria may be relevant for items that are difficult to quantify, they also allow different persons to have varying opinions on the quality of the simulation. To avoid such a situation, specific guidelines should be provided on what constitutes an acceptable model.
- **Calibration of turn volumes at intersections** – While most of the reviewed CSMP modeling efforts sought to calibrate simulated link flows to observed values, not all efforts examined the correspondence between simulated and observed turn volumes at intersections. Simply verifying that link flows on intersection approaches are adequately replicated does not ensure an accurate replication of turn volumes and queues at intersections.
- **Definition of links for travel time calibration** – There is no standard approach for the calibration of link travel times. While some of the modeling efforts attempted calibrating travel times across segments covering only the distance between adjacent intersections, other efforts attempted to calibrate end-to-end corridor travel times. While short segments allows for a more refined calibration, they also requires more work. In addition, there may not always be enough field observations to support this level of analysis. On the other hand, considering only corridor-wide travel times is too coarse, as this approach may not lead to a correct replication of bottlenecks. Ideally, a segmentation matching available data, such as between PeMS stations, or matching operational considerations, such as from one bottleneck to another or between major interchanges, should be adopted.
- **Calibration against limited travel time data** – Many modeling efforts relied on relatively small data samples to calibrate travel times across individual segments. At issue here is whether data from 10 or 20 runs collected over 2 or 3 days provide a reliable sample against which to calibrate a model. A more specific question is whether the travel times provided by such a sample should be closely replicated or simply used as a reference to test whether the simulated travel times are reasonable. While collecting more travel time data can be ideal, doing so can also have significant implications on the required modeling resources.

- **Gaps in geographical data coverage** – While many freeways have PeMS stations every half mile, longer spacing may exist on some freeways. Stations down due to maintenance activities or technical problems may also create longer gaps. Where large gaps exist, particularly larger than a mile, caution should be exerted to avoid assuming that data collected from surrounding stations necessarily reflect operational conditions that should exist between the two stations.
- **Calibration of base year model using data from prior years** – For some corridors, the demand for a given base year was calibrated using data from prior years. This can create problems as prior year patterns may not necessarily match patterns in later years, particularly if improvements have been made to the network or other environmental factors have changed. If data for the modeled year is available, it should be used for the development of the travel demand pattern. Otherwise, the most recent data should be used and, if possible, adjusted to reflect known trends in travel patterns or changes in travel demand.
- **Checking for unreleased vehicles in simulation model** – Unreleased vehicles are vehicles that are unable to enter a network due to congestion on entry links. While it is reasonable that queues of unreleased vehicles develop on occasion, such queues should dissipate quickly. Long queues can create better than expected conditions within the network by artificially reducing the simulated traffic. In addition, many models will not compile statistics from unreleased vehicles, thus further affecting the performance measures. A potential for bias also exists if the improvements being simulated result in more vehicles being released. More released vehicles could increase the total delay being compiled, even though the delay per vehicle may be lower. Due to these potential impacts, many task orders included a requirement that model parameters be adjusted "to ensure that all vehicles can be released into the network". However, this requirement did not stipulate whether it pertained to each simulation hour or the entire simulation, thus making it acceptable for long queues of unreleased vehicles to develop in the middle of a simulation as long as they fully dissipated by the end of the simulation.
- **Frequency and handling of stalled vehicles within simulation model** – There is not enough evidence to determine the extent to which modeling teams checked whether vehicles artificially stalled due to coding problems or whether an excessive number of such vehicles were removed from the simulation by automated filters. In the first case, stalled vehicles can create artificial congestion, and thus negatively bias simulation results. While removing stalled vehicles in the second case may prevent artificial congestion, this process can artificially reduce the traffic demand. To address this issue, some task orders included a requirement that no more than 500 vehicles be removed from the simulated network. There is also evidence that this modeling criterion was checked by some reviewers. However, modeling reports do not provide statistics for this issue. It cannot be required that no vehicle be removed, as the removal of a few stalled vehicles can contribute to simulation stability while only marginally affecting simulation results. However, the frequent removal of stalled vehicles from a given location would be an indication of coding problems that must be addressed.
- **Documentation of model changes** – It is good practice to document all changes made to a model during its calibration. This not only helps reviewers understand what has been done, but also individuals tasked with future model maintenance.

Model validation is technically a different step than model calibration. From a theoretical standpoint, calibration focuses on the adjustment of model parameters to match observed conditions while validation consists of the application of a model to new conditions to ensure that it can safely be used to evaluate untested conditions. Typically, model calibration is done by adjusting model parameters such that a reference set of conditions is adequately replicated. To validate the model, different input parameters based on data that had not been used for the calibration are inputted into the model. The results of the simulation are then checked to ensure that reasonable traffic conditions are still produced.

The distinction between calibration and validation was not made clear during the CSMP modeling efforts. Many documents simply refer to "calibration and validation" efforts. In most cases, the efforts documented are strictly calibration efforts. However, this is not to say that validation efforts were not conducted. In many cases, validation activities were implicitly conducted as part of the Phase 2 and Phase 3 reviews. This is an area that can benefit from further clarification.

8.9. SCENARIO DEVELOPMENT

The following are important issues to consider regarding the development of evaluation scenarios:

- **Impacts of time and budget constraints** – While an ideal situation would be to evaluate all possible combinations of improvements, such an exhaustive approach is generally infeasible due to budget and time constraints. Considering every possible combination can lead to hundreds, if not thousands, of evaluation scenarios, with each further requiring multiple runs if using a stochastic model. Most modeling projects will have insufficient time and/or resources available to evaluate all possible combinations, thus creating a need to either reduce the number of improvements considered or to develop group improvements to be evaluated together.
- **Identification of baseline scenario** – In many cases, it is unrealistic to begin evaluations with a road network only reflecting the existing roadway geometry and traffic management systems. Often, it makes sense to include improvement projects that are already under way and projects that are expected to be completed by the time model development will be completed.
- **"Do minimum" horizon scenarios** – When developing horizon scenarios, some modeling teams included already programmed improvements or improvements that would be required to maintain a reasonable level of service in the horizon baseline. This approach makes sense only if the goal is to evaluate improvement projects beyond those included in a "do minimum" scenario. CSMPs were meant to get ahead of the programming decisions and evaluate whether any potential improvements would be beneficial before programming them. However, because of longer than anticipated model development, some projects were eventually committed before the evaluations could be completed, thus resulting in their inclusion in the "do minimum" horizon scenario while the original intent was to evaluate them prior to their inclusion.
- **Impacts of model development time on set of candidate improvements** – While it often makes sense to identify early a set of candidate improvements to evaluate since the selected improvements may affect the scope of the modeling effort, it should be kept in mind that the selected set of improvements may change as a result of the time required to develop the simulation model. As an example, many CSMP modeling efforts took upwards of two years to develop a calibrated base model. In one corridor, some projects that were originally planned to be implemented by 2020 were pushed further out in time before the model was completed, thus removing the need for their inclusion in the evaluation scenarios. While an initial set of improvements projects can be identified to help with model scoping, this set should not be finalized before a base year calibrated model is obtained.

- **Strategy for bundling projects** – Many CSMP task orders limited the number of evaluation scenarios. For most corridors, it was also inconceivable to evaluate every possible combination of improvements. To conduct evaluations within reasonable time and budget, candidate improvements were frequently bundled into groups that would be evaluated together. While this approach resulted in fewer scenarios to evaluate, it did not allow for assessing the impacts associated with specific improvements. Careful consideration should thus be given to developing logical rules for determining whether particular improvements should be evaluated separately or as part of a bundle and, in the latter case, with which projects.
- **Strategy for developing relevant evaluation scenarios** – Evaluation scenarios were generally developed by appending improvement bundles to a baseline scenario. In many cases, a simple additive process was followed to develop alternative scenarios. New improvement bundles were simply added on top of those considered in previous scenarios. While this approach mimicked a staged deployment, it has been criticized by some for potentially locking the evaluations into a predetermined sequence of projects that may not be optimal. While an ideal approach would have been to evaluate each combination of bundles, this would have not often been possible. This thus created a need to reduce the number of scenarios by developing logical sequences of implementation of improvement bundles.
- **Documentation of bundling and evaluation strategy** – The rationale that was considered for determining the bundling of scenarios and the sequence in which individual bundles should be evaluated was not always clearly described. An understanding of the rationale and rules behind the bundles would have helped reviewers and individuals using simulation results better assess the context in which the evaluations were made.
- **Consideration of corridor-specific context** – While the temptation exists to recommend the development of generic guidelines for the definition of improvement bundles and scenarios, this may be difficult to do due to the varying improvement needs and operational constraints that can affect each corridor. Developed project bundles and scenarios should always make sense in their regional context.

8.10. REVIEW PROCESS

The following are important issues regarding the model review process that were identified:

- **Consistency of review process** – The application of a consistent review process is important to ensure that all simulation models are being developed against similar standards. The current phase of CSMP operational evaluations provided a first attempt in this direction through the implementation of standard calibration guidelines, the recommended application of a three-phase review process, and the development of a standard peer review checklist. However, due to various reasons, staff from individual Districts did not always follow the recommended process. This resulted in an unequal review process across various Districts.
- **Technical model review versus model calibration review** – A model review technically involves two specific tasks. The first task is a technical review to check whether gross coding errors are present within the model. The second task then checks if the simulated flows match observed behavior. In the CSMP review process, reviewers were generally asked to simultaneously check for errors and calibration issues during the initial review. A better approach could have split the review into two phases, asking reviewers, for instance, to only start the calibration review after a model has been checked at least once for significant coding errors.

- **Technical knowledge of reviewers** – Individuals tasked with the review of simulation models should have an adequate knowledge of traffic simulation principles and/or technical capabilities of the simulation tool being used. Individuals tasked with reviewing the technical aspects of a model should further have a basic knowledge of simulation modeling principles and of the audit tools available within the model. Individuals tasked with assessing whether the simulation model adequately replicate observed conditions should also have certain knowledge of traffic conditions and typical driver behavior for the network being modeled.
- **Tracking of modeling issues** – All the issues that are uncovered during a model review, as well as the modifications made to a network to address these issues, should be documented. For those cases where no changes were made in spite of a modeling issue, an explanation should be documented. This will not only allow for greater transparency of the review process, but help track what has been done to resolve issues. This documentation can prove particularly valuable for individuals who may be tasked with the model maintenance in the future.
- **Use of review process as quality control set** – In some modeling efforts, consultants submitted flawed models for review that lacked appropriate quality assurance and quality control measures. In some cases, the perception from reviewers was that modeling teams were overly relying on the initial model review to help identify and correct simple mistakes. This practice not only extended the time reviewers spent assessing the submitted models but also unfairly shifted some of the model development burden to the reviewers.

8.11. MODEL APPLICATION

Critical issues related to model applications include the following:

- **Determination of number of runs required** – Due to the stochastic nature of microscopic and mesoscopic models, multiple runs with different random number seeds must be conducted to evaluate scenarios. While this requirement is generally recognized, the number of runs is often based on prior experiences rather than the stochastic variability of simulation results. A frequent practice appears to do 5 or 10 runs. For one corridor, evaluations have even been conducted against a single run of a microscopic model. This is a case where too few runs were likely considered. Each evaluation should include a justification for the number of runs executed. This can be done by contrasting the number of runs executed against the number of runs required to achieve a certain statistical accuracy based on the observed variability of simulation results. Since this approach has been known to return a high number of runs for networks with sizable variability, it could be permissible to conduct a smaller number of runs if an appropriate justification is provided.
- **Selection of simulation time step** – The time step used to move a simulation forward can impact the evaluations, particularly when simulating highly congested networks. By allowing drivers to react more frequently to surrounding traffic and hazards, using shorter time steps can create smoother traffic behavior and higher effective capacity. However, short time steps will also increase run times. In some cases, they may also only create marginal improvements, if any. For these reasons, the ideal time step will likely vary from case to case. Because of this, the rationale behind the selection of a particular time step should always be documented. This was not always the case for the CSMP operational evaluations.
- **Balancing short time steps and resulting run time** – Because shorter time steps will increase simulation time, an adequate balance must be reached between the time step and the time

available to evaluate all scenarios of interest. In many cases, the higher computational loads associated with shorter time steps can be partly compensated through the utilization of batch simulation modes, which allow sets of simulations to be executed without any graphical elements. Some models also allow simulation computations to be distributed among a group of computers for faster execution.

- **Inadequate reporting of model application parameters** – There was no consistent reporting of how the simulation models were used to evaluate improvements. Details on the number of conducted simulation runs, the duration of the warm-up period, the demand loaded onto the network during the warm-up period, and the selected time step are missing from many modeling reports. While many of these elements are only of interest to modelers and project managers, their knowledge is crucial for judging the quality of the simulation results since different simulation setups can affect the simulation results.

8.12. EVALUATION OF SCENARIOS

The following are specific issues that were encountered or identified regarding the ability to evaluate scenarios and generate performance measures of interest:

- **Linking corridor objectives to performance measures** – It is important is to determine the objectives sought for the corridor improvements prior to conducting any evaluation, and to link these objectives to specific performance measures. The relative importance of each measure and criteria should further be determined and agreed upon by all project stakeholders. Documenting these elements before starting an evaluation will add clarity to the process and help ensure that the evaluation process follow its initially intended purpose. Such a process was not always followed during the CSMP evaluations. As a result, performance ranking and project prioritization were frequently solely based on operational benefits that may not have adequately reflected other corridor management objectives.
- **Identification of comparison criterion** – Several methods can be used to compare the benefits provided by proposed improvement projects. Two examples include the cost-benefit analysis (CBA) and the cost-effectiveness analysis (CEA). Ideally, a standard comparison method should be applied to all CSMPs. However, this may not always be possible due to the potential for differing objectives across different corridors. Similar to other aspects of a modeling project, there should be adequate documentation of the rationale behind the selection of a particular comparison method.
- **Availability of desired performance measures** – A challenge with many simulation models is to ensure that the performance measures produced match desired measures. For instance, while all simulation models output included delays, this measure may not necessarily be calculated as defined by the client agency. By default, simulation models use the posted speed limit or the desired speed of a driver as reference. Caltrans, on the other hand, typically calculates delay against a 60 mph reference. Expectations must therefore be adjusted. If it is desired to compile delay differently than what is done by the simulation model, the adjusted delay could be reconstituted through post-simulation data processing or estimated directly through the use of custom plug-in modules. However, these options introduce additional tasks that can affect time and resource needs.

- **Consistency of segmentation approaches** – Different segmentation approaches were followed to report performance measures. Some corridors compiled measures for segments extending between key interchanges while others defined segments in relation to bottlenecks.
- **Performance measures reported** – Across the CSMP corridors, simulation results were typically used to assess incurred delays. Other performance measures that may be of interest to decision-makers, such as average travel times or speeds, were not always reported in the final reports, even though they were likely outputs from the simulations.

8.13. PRIORITIZATION OF IMPROVEMENTS

Operational benefits estimated from simulation results were used in all corridors to help determine the most effective projects, and in some cases, provide recommendations on when specific projects should be implemented. Projects producing the highest benefit/cost ratio with the largest potential to reduce queuing and congestion were generally placed high in the list of recommendations. In some cases, projects that had been found not to be required by a certain year were recommended for later implementation. Finally, there was no example of projects being removed from consideration as a result of a lack of impacts on corridor operations.

Final decisions regarding which projects to implement were generally left to the decision-makers. In this case, decision-makers should always exercise caution when making investment decisions based solely on simulation results, particularly for projects that may commit millions or billions of dollars, since the simulations only provide estimates of potential benefits. Final project decisions should be based on a combination of regional and inter-regional needs, regional and local acceptance for the selected projects, compatibility with the regional transportation planning goals, funding availability, technical feasibility, and deployment requirements.

8.14. DATA PRESENTATION

The following critical issue was identified regarding the ability to use simulation models to generate information supporting decision making activities:

- **Ability to generate animations** – Several decision-makers and project managers indicated that the ability to generate animations was an important or crucial feature. While transportation professionals can rely on their expertise to make sense of an array of parameters, individuals lacking a similar expertise may not do so. In this context, animations can provide a powerful means to visualize the impacts of proposed improvements in a manner accessible by a lay audience. A specific preference is towards developing animations capable of showing the movements of individual vehicles, i.e., from either microscopic or mesoscopic models.

8.15. PROJECT DOCUMENTATION

The following issues were identified regarding the documentation of modeling and simulation efforts:

- **Lack of report uniformity** – While CSMP reports appeared to have followed a general template, there was no uniformity in the information presented, particularly regarding the description of simulation efforts. Some consultants provided detailed information and others relatively little.

While it was often possible to find modeling and model utilization information in separate reports or technical memos, a better approach would have been to provide key information detailing the model development, its calibration, and its use within the main CSMP report.

- **Lack of report completeness** – Reports detailing modeling efforts should contain enough information to allow another experienced modeler to understand what has been done. All model assumptions and any coded special features should be documented. None of the modeling reports that were reviewed fully described the modeling efforts. While some reports were more complete than others, additional information about modeling tasks had to be retrieved from technical memos and interviews with modelers.

8.16. MODEL MAINTENANCE

Ideally, the simulation models that have been developed as part of the CSMP program should be made available for other evaluations. This would allow the time and resources that have been dedicated to the development of these models to contribute to other projects, thus yielding a higher effective return on the investment that has been made. However, Caltrans currently does not have a formal program or guidelines for the maintenance of developed simulation models. In addition, various Caltrans District staff already question whether simulation models will continue to be used to support future CSMP operational evaluations, thus creating further uncertainty regarding future uses of developed models.

Model maintenance would not only allow developed models to be applied towards other projects, but also allow the knowledge that was developed regarding the development and use of modeling tools to be better retained. In this context, elements critical to the development of an effective simulation model maintenance program include:

- Adequate budget allocations supporting model maintenance needs.
- Availability of software licenses for all simulation platforms that have been used, to enable access when needed to all the simulation models that have been developed.
- Availability of trained personnel who understand the principles behind the various models used and the issues associated with individual corridors. These can be either Caltrans staff or on-call external consultants. In the latter case, however, an emphasis should be put on contracting individuals having adequate knowledge of the regional transportation network.
- Process to track roadway geometry and operational changes along a corridor between evaluation projects and to log updates that have been made to the corresponding simulation model. Model changes can be made at periodic intervals or each time a new evaluation project is initiated. Regardless of the approach adopted, logging required model updates between periods of utilization of a model would allow determining the magnitude of the work needed to bring a model up to date at the start of a project, as well as better allocating available resources.
- Periodic re-calibration of developed simulation models, not only to address traffic demand or road geometry changes, but also changes in simulation logic introduced with the release of new software versions. In particular, there should be an understanding that these re-calibrations will likely require additional time and budget to collect and process new data, implement changes within the simulation model, and conduct new model audits. A suggestion is to link the model maintenance process with the existing transportation system planning cycle.

- Understanding the need for the simultaneous maintenance of planning and traffic simulation models. Changes to the regional travel demand model should be reflected in the traffic simulation models for the modeled area. Conversely, relevant changes made to the simulation model should be propagated back to the regional travel demand model.
- Appropriate documentation of all modifications made to individual models, detailing when the modification was made, what was changed, and why the change was made.

An additional need is to determine which Caltrans Division would be responsible for managing the simulation models. While the Division of Transportation Planning has been leading the development of CSMPs and their corresponding simulation models, District and Headquarters staff from the Division of Traffic Operations played a major role in the operational evaluations. These individuals provided data and technical expertise for major components of the CSMP operational evaluations, such as performance assessment, bottleneck analysis, causality analysis, network coding, calibration audits, and selection and testing of improvement scenarios. The Division of Transportation Systems Information (TSI) has further recently been put in charge of the Traffic Accident and Safety Analysis System (TASAS), which provided the safety data for CSMPs. It has also been providing support, including training and licensing, for microsimulation models other than Paramics. Given their respective involvement, these three agencies would need to decide jointly how and where to archive the developed simulation models and determine how the models can be made available to anyone within Caltrans wishing to utilize them.

9. LESSONS LEARNED

This section provides a summary of key lessons that were learned during the CSMP modeling efforts. These lessons learned are summarized according to the following categories:

- Positive experiences;
- Negative experiences; and
- Lessons learned regarding specific simulation modeling activities.

9.1. POSITIVE EXPERIENCES

The following are positive experiences that were expressed by individuals who were contacted by the project team regarding the use of simulation models for supporting CSMP operational evaluations:

- Calibrated models were successfully developed within the initially allotted time and budget for many corridors.
- A majority of surveyed individuals indicated that the modeling efforts met initial expectations and accurately fulfilled their intended role.
- Simulation results have been influential in many cases in affecting investment decisions, helping for instance, to determine which projects should be pursued and to prioritize improvements.
- The traffic simulation models helped planners, designers and traffic engineers obtain quantitative assessments of the potential benefits that may be obtained from potential corridor improvements. In particular, the models often allowed factoring complex interactions between road geometry, driver behavior, control devices, and traffic management strategies that would have been difficult to consider using other tools, such as the Highway Capacity Manual.
- In many cases, the visual animations that were extracted from the microscopic simulation models have been instrumental in helping decision-makers in understanding the problems affecting a corridor, assessing the benefits provided by proposed improvements, and making sound investment decisions.
- While challenges were encountered in explaining to decision-makers or project managers why simulation results sometimes differed from expectations, the dialogues that developed around these challenges often led to a better understanding of the desirability of specific improvements and the identification of new potential improvements. In some cases, the discussions even led to the establishment of improved decision-making partnerships between stakeholders.
- The modeling efforts provided an opportunity and an environment in which professionals from various areas worked closely and exchanged information. This environment facilitated the building of knowledge, technical and managerial skills, and professional expertise regarding the use of simulation as an evaluation tool. There has also been a positive influence in making sure that research and development activities lead to the production of useful products fulfilling the needs of real-world applications.
- Upon completion of its remaining CSMP study, Caltrans District 12 will be the first one to have used microsimulation to evaluate all of its major regional freeway corridors.
- Simulation models are now available to support non-CSMP projects along many corridors.

- The existing simulation models should provide a good starting point for the next cycle of CSMP operational evaluations. The ability to start future evaluations with already-developed models should allow future CSMPs to be completed in less time and with smaller budgets.

9.2. NEGATIVE EXPERIENCES

While many positive experiences were reported regarding the use of traffic simulation models to support CSMP evaluations, some negative experiences were also recorded:

- Many individuals commented on the fact that the development of traffic simulation models was a high-cost, time-consuming task highly dependent on consultant services.
- Many individuals commented on the complexity of calibrating microscopic simulation models covering large and/or complex road networks.
- In some Districts, thousands of hours were spent by Caltrans staff reviewing, correcting and commenting on models that were eventually not well calibrated. This has led to a perception by some individuals that Caltrans interests might have been better served if the agency staff had instead received advanced modeling training and conducted the modeling in-house.
- In two of the 31 CSMP simulation modeling efforts, Caltrans only received a partially developed model. A calibrated model failed to be developed after several years of reviews and comments due to the complexity of the road network that was being modeled.
- Calibration difficulties led one consultant to abandon the modeling of one corridor, after most of the allocated funds were expended. The corridor was deemed too large to be calibrated, even after segmenting it into smaller networks. While Caltrans staff expressed concern early in the project that the size of the attempted modeling would lead to calibration difficulties, this concern was dismissed by the hired consultant.
- Some calibrated models provided questionable simulation results or results that made no engineering sense when running scenarios other than the calibrated baseline.
- In at least one case, the CSMP project team was unable to provide substantive and sufficient data or performance measures to sway political opinion in the time needed.
- Only one of the four attempted TransModeler hybrid microscopic/mesoscopic modeling efforts produced a model that eventually supported CSMP operational evaluations. Calibration difficulties led two modeling teams to develop a microscopic-only TransModeler model. For the third corridor, District staff opted instead to develop in-house a FREQ 12 macroscopic model. While one hybrid model was successfully used, concerns still linger regarding its ability to accurately replicate traffic behavior. However, it should be noted that these experiences do not necessarily mean that a hybrid modeling approach is inadequate, as the above efforts were first attempts at developing hybrid models and as they further relied on relatively untested functionalities of TransModeler. It is therefore possible that some of the problems that were encountered have since been resolved.
- Some of the above negative experiences have led some individuals within Caltrans to question the effectiveness of using microscopic or hybrid microscopic/mesoscopic models as evaluation tools for freeway operational evaluations and to advocate instead for the use of macroscopic models or analytical tools.

9.3. LESSONS LEARNED REGARDING SPECIFIC MODELING ACTIVITIES

This section outlines lessons that were learned regarding the capabilities of simulation models, model development and calibration needs, and the use of simulation to conduct operational evaluations:

- **Perceived capabilities of simulation models:**
  - Project managers and decision-makers must have realistic expectations regarding the capabilities of traffic simulation tools. Although there has been significant progress in microsimulation capabilities, limits still exist. For instance, while many models now offer tools to model HOV/HOT lanes or variable speed limits, largely in response to a growing interest in such applications, these new features have not yet fully matured. Until refinements are introduced by model developers, the adequate replication of some systems will require the use or development of custom plug-in modules using a model's Application Programming Interface (API). It is also possible that some novel applications cannot be modeled.
  - Project managers and decision-makers must understand that simulation models are only as good as the data used for their development. While inaccurate data will not prevent the development of a model, it will allow it to provide inaccurate results that may subsequently lead to sub-optimal or wrong decisions.
  - The inherent complexity of developing simulation models introduces significant risks to an evaluation project. Examples of risks that must be considered include the potential need for collecting more data than initially anticipated, longer than expected development times, and potential difficulties in obtaining a calibrated model.
  - While many models have been developed within the allotted time and budget, this will not necessarily be the case. Inadequate or problematic data, as well as complex modeling tasks, may cause calibration difficulties that can push a project beyond its initially planned scheduled.

- **Staffing/professional capability needs:**
  - While external consultants were contracted to perform the modeling and evaluations, Caltrans staff from the Division of Traffic Operations often played a major role in developing and preparing the simulation models. Division staff provided data and technical expertise for major project components, such as performance assessment, bottleneck analysis, causality analysis, network coding, calibration audits, and improvement scenarios selection and testing.
  - The level of experience of the modeling team in using a specific model can significantly affect the time and resources needed to produce a calibrated model, particularly for corridors with complex features. Highly skilled teams can spot earlier problems that are due to input data or network coding, and thus initiate steps to resolve the identified issues before too much time or resources are expended.
  - In addition to knowledge of the simulation tool being used, the development of simulation models and the evaluation of operational improvements require the involvement of individuals with a comprehensive knowledge of simulation modeling principles, traffic flow theory, and traffic control principles.

  - There are currently a limited number of Caltrans employees who have the extensive knowledge of simulation modeling principles that is necessary to effectively utilize simulation tools. This creates limitations in the ability of some District offices to fully assess the needs and issues associated with simulation studies.

- **Selection of modeling approach and modeling tool:**
  - Some CSMP evaluation teams attempted to evaluate corridor operations using newly released simulation tools for which there have been limited prior applications. While the selection of such tools have provided access to capabilities not yet offered by other simulators, using tools with a limited track record may have opened the door to additional modeling difficulties, in addition to requiring added time to learn how to use the model. Newly developed tools can also have residual coding bugs that are affecting simulation results and that may take time to be uncovered and corrected by the software's development team.
  - The interest of some modeling teams in using a hybrid microscopic/mesoscopic simulation approach was mainly driven by a desire to try to capture a greater travel shed around the modeled freeways. In many cases, a hybrid modeling was adopted as an attempt to better capture the potential route diversion effects and resulting operational changes on roads surrounding the modeled freeway associated with the improvement strategies considered, particularly dynamic tolling and managed lane strategies.

- **Modeling scope:**
  - The geographic scope and complexity of a road network significantly affects the time and resources needed for model development and calibration. In addition to additional data collection needs, longer corridors involve the development of large O-D matrices that are inherently more difficult to calibrate.
  - While it was initially intended to develop a single model for each corridor, the complexity of the task led some teams to develop separate models for different sections. Corridor splits were justified to shrink the schedule for model development and scenario evaluation by allowing parallel development tracks or facilitating model calibration.
  - Networks can be effectively broken up into smaller networks at low volume points between bottlenecks. Regardless of the approach followed, networks should not be split so as to limit the geographical extent of the zone of influence of bottlenecks.
  - Modeling signalized arterials tends to be more demanding than the modeling of freeway sections and ramps. This is not only due to the need to collect more types of data, such as turning counts, timing plans and queue statistics, but also to the fact that arterials are less contained environments. While freeway traffic is restricted to enter and exit at a few locations, there are multiple possible entry/exit points along arterials. This situation often leads to discrepancies in collected data and difficulties in adequately replicating arterial traffic patterns. There are also larger data gaps along arterials due to a historical preference to deploy traffic monitoring systems along freeways.
  - There is still uncertainty regarding the ability of traffic simulation models to adequately replicate route selection in networks offering multiple paths. While existing models can

model route selection based on travel time, travel distance, and out-of-pocket costs, many other factors often considered by travelers are still not considered. An example is activity chaining, in which travelers select a particular path based on a need to execute various tasks in succession, such as the need to pick up children from school and then to stop at a grocery store on their way home from work on a particular day.

- **Data collection:**
  - Poor or inaccurate data introduces significant risk to a simulation evaluation. All supporting data should therefore be properly validated before it is used. While such a requirement may impose an extra step at the beginning of a project, it can reduce the number or magnitude of problems that may be encountered later.
  - Imposing limitations on the data collection budget or period can significantly impact the quality of the simulation model being developed, particularly when using microscopic or mesoscopic models since these models generally require more comprehensive data to be collected than macroscopic models.
  - Data collection needs for the development of simulation models can inform the development of more effective guidelines on the installation of traffic detectors along freeway mainlines and ramps. The data needs may also help prioritize the maintenance of existing sensors.
  - Minimum detection data needs for the development of simulation models include:
    - Collection of traffic data at modeled ingress and egress points; this generally corresponds to the current practice of installing detectors on the freeway mainline at interchanges, on-ramps to support ramp metering, and off-ramps where relevant.
    - Collection of data downstream of bottlenecks to measure flow output.
    - Reasonable detection coverage between interchanges. The current practice of installing mainline detectors every 0.5 mile often leads to the installation of several stations between interchanges. While a high density of detectors helps track the evolution of congestion, simulation models typically only require data from one station. Where resources are limited, an efficient approach may be to only maintain a few strategically placed stations between interchanges, except where bottlenecks or other operational conditions warrant more.
  - Not verifying the validity of the data that have been collected by a modeling team or provided by third-parties can introduce significant risk to a project, particularly if erroneous or inaccurate data end up being used for model development or calibration.
  - A best practice is to identify at the start of a project what data is available and what data will need to be collected to support model development. The data collection plan should further distinguish what data that will be required for the development of the road network and the modeling of the traffic demand and what data will further be required to test the validity of the model.
  - Data collection should not only focus on the need to develop a calibrated base year model, but also on the need to subsequently develop suitable evaluation scenarios.

  - While tachometric runs were often conducted to collect information about travel times where this information could not be obtained from other sources, the relatively limited number of runs that were executed for many corridors casts some shadow on the ability of the collected data to be effectively used for calibrating simulation models.
  - Using limited data samples for model development and calibration can introduce significant uncertainty regarding the validity of a resulting model, particularly for networks experiencing significant day-to-day variations in traffic conditions. Ideally, sufficiently large data samples should be collected to ensure that the extracted information adequately reflects the conditions being modeled. However, there remains uncertainty on what constitutes an adequate sample size. Data collection needs are likely to change from corridor to corridor. Guidelines are thus required to determine the extent of the required data collection efforts for each modeling project.
  - While a statistical analysis can be conducted to estimate a sample size satisfying a given confidence level, such analyses often indicate that more than 100 runs should be conducted for evaluating segments with high traffic variability. While obtaining such a large sample is feasible with automated traffic monitoring systems, such as license plate matching systems or systems tracking Bluetooth devices, it may be too costly and time prohibitive when using traditional tachometric runs. Until improvements in data collection methods are achieved, compromises will likely need to be made regarding how much data should be collected to support model development.
  - Collecting data from non-centralized sources can be a significant endeavor. Benefits may exist in having a unit within Caltrans Districts specifically tasked with gathering, validating, processing, and distributing traffic operational data to modeling teams.

- **Travel demand modeling:**
  - The development of realistic and reasonably accurate O-D trip patterns is a key factor in enabling a simulation to replicate observed traffic conditions with fidelity.
  - Where available, regional travel demand models were commonly used as the primary source of information for the modeling of trip patterns. Where such models were not available, trip patterns were instead primarily developed from flow counts and turning counts using synthetic O-D matrix estimation (ODME) techniques.
  - While travel demand models can provide regional trip forecasts based on land use and socio-economic factors, the trip patterns extracted from such models cannot necessarily be transferred as is into traffic simulation models. The utilization of more refined trip zonal systems within traffic simulation models will often require the travel demand forecasts to be manually distributed across a set of smaller zones. Furthermore, since demand models generally forecast trips on a simplified road network, there can be notable differences between the forecasted and actual trip patterns along the corridor. It is therefore important that appropriate checks be made to ensure that representative trip patterns are extracted from travel demand models. Not doing so can lead to various problems during the calibration of a traffic simulation model.
  - Attempting to disaggregate zonal trip patterns within a travel demand model is more effective than doing so within a traffic simulation model. The approach involves creating within the regional demand model a subarea with added detail pertaining to the simulation study area. Outside of the study area, the defined traffic analysis zones

do not change. The zones inside of the area are split into as much detail as necessary to accommodate the zones defined in the traffic simulation model. This may also involve adding links where necessary. The updated travel demand model is then run to extract trips crossing the study area. This approach has been found to save time, since it is more efficient to adjust the demand model than the traffic model, and since there is no need to manually adjust O-D tables. It is also thought to provide better accuracy, since the potential for human error and bias in distributing trips across sets of smaller zones is removed.

- An ideal situation when developing a simulation model is one in which the simulated base year matches the base year of the regional travel demand model. However, since demand models are typically updated once every 4 or 5 years, there is a reasonable probability that the desired base year for the simulation model will not match the one defined in the travel demand model. In such a situation, an approach sometimes adopted is to change the simulation base year to that of the travel demand model. While it simplifies the development of O-D matrices, it also produces an outdated simulation model that may not adequately reflect actual traffic patterns. Since trip patterns from travel demand models are themselves estimates, it is more logical to try to update the forecasted trip patterns to current conditions than to force the development of an outdated model.
- Many simulation models offer tools allowing O-D matrices to be developed from link flow and intersection turning counts. These tools can be used to develop O-D matrices from scratch or to refine matrices derived from travel demand models. However, they do not guarantee that the resulting trip patterns will necessarily replicate observed patterns since the observed flow and turning counts can be replicated with various combinations of trips. This is an area of significant ongoing research.
- While trips made by passenger cars, high-occupancy vehicles, trucks, and in some cases buses, were generally distinguished, there were variations in how vehicle-specific trips were generated. Some models defined specific O-D flow matrices for each vehicle type while others simply apportioned the total flow between each O-D pair based on predefined vehicle proportions. While the first approach is preferred, as it provides greater flexibility in assigning or restricting travel between specific O-D pairs, it is also dependent on the availability of sufficient vehicle classification data to allow a detailed analysis of vehicle movements across the various parts of a network. Unfortunately, many modeling teams only had classification counts from one or two locations at their disposal, which then pushed them towards the second, less accurate approach.

- **Model development:**
  - Various factors in addition to the length of a corridor affect the potential duration and cost of a simulation modeling effort. Key influencing factors are:
    - Differences in geographical scope, such as length of corridor and extent of modeling of surrounding arterials;
    - Differences in road network complexity, such as proportion of curved roadway segments, number of complex interchanges, presence of HOV lanes, ramp meters, and ITS applications;
    - Ability to reuse previously developed models;
    - Differences in the quantity and quality of available data;

    - Number of bottlenecks and complex merging/weaving sections to model;
    - Expertise of project team in handling and resolving complex modeling and calibration issues; and
    - Number and complexity of scenarios to be developed and evaluated.

- **Model calibration:**
  - Documenting the real causes of congestion is a key element of model calibration. Knowing the causes of operational problems not only helps ensure that observed problems are appropriately replicated but also helps stakeholders accept how proposed improvements will help resolve the observed problems.
  - Adequate replication of bottleneck is generally recognized as a key calibration target. Despite this importance, the FHWA/Caltrans guidelines only provide vague targets for this matter, simply stating for instance that bottlenecks must be calibrated "to the analyst's satisfaction". Because of its subjective nature, the current guideline can lead to diverging opinions on when a model has reached an acceptable calibration status. Quantifiable targets are needed to help ensure consistency in model development and objectivity in the review process.
  - For many corridors, a key element regarding the calibration of bottlenecks was to ensure that the simulated traffic speeds matched observations where field data were available. A potential danger is to overlook operational conditions between the observation points. Calibrating simulation models based on a comparison of speed profiles is acceptable as long as the gaps between successive observation points are not too large. Where longer gaps exist, the approach would also be acceptable if it can be demonstrated that traffic conditions between the detection stations are similar to those observed at the stations. If uniformity of traffic conditions cannot be demonstrated, alternate or additional calibration criteria should then be considered.
  - A suggestion brought forward by some individuals is to exclude all links belonging to a bottleneck from being counted towards the 15% of links allowed to have flow deviations exceeding the calibration target. Doing so would prevent modelers from relying on the 15% error allowance to justify the presence of improperly calibrated bottlenecks.
  - The current FHWA/Caltrans guidelines regarding the replication of individual link flows do not provide a consistent standard. While it is recommended that simulated flows be within 15% of observed flows for links carrying between 700 and 2700 vph, a fixed 100 vph deviation is allowed for links with less than 700 vph and a fixed 400 vph deviation for links above 2700 vph. These guidelines create a relaxed standard for low-volume links and a tighter standard for high-volume links. While it is logically desirable to ensure that high-volume links are correctly simulated, the low error tolerance can lead to difficulties attaining the calibration targets for networks featuring high-volume links. On the other hand, the larger error tolerance for low-volume links may allow a relaxed calibration for important low-volume links, such as HOV lanes.
  - The current FHWA/Caltrans calibration guidelines were specifically developed for microscopic modeling efforts. Adjustments may be required to apply the guidelines to macroscopic, mesoscopic or hybrid modeling efforts. For instance, hybrid models may require special emphasis on the links at the boundary between the microscopic and mesoscopic areas to ensure that excessive queues do not develop there.

- To address discrepancies among data collected from various sources, the collected field data are often adjusted to obtain more balanced datasets. While this approach reduces discrepancies, it also carries the risk of producing data that may not fully match observed traffic conditions. Another risk is to use inaccurate data for model calibration. While flow balancing is a conceptually valid approach to address data problems, it must be recognized that it artificially alters field data. Balanced data should therefore carry less weight than unaltered data in model development and calibration. Consequently, any data that have been balanced should be clearly identified to allow subsequent users to know its true origin and accuracy.
- While there was no requirement to apply the calibration targets separately to each simulation hour, many CSMP modeling teams did so. This is a better practice, as it ensures a consistency of calibration over the entire simulation period. Simply applying the targets over the entire peak period only ensures that average operational conditions are adequately replicated over the peak period and can leave significant divergences within specific intervals. Calibrating a model for each interval further ensures that it can be used for conducting evaluations over intervals that may be shorter than the initial modeled period.
- The existing FHWA/Caltrans calibration targets do not adequately address traffic movements along arterials. This is exemplified by the lack of formal calibration targets for turn volumes at intersections. Strict application of the current guidelines can lead modeling teams to adequately replicate the total volume on the approaches to intersections, but not necessarily the individual turn movements. To avoid such a situation, calibration targets addressing arterial-specific elements should be developed. As an example, the draft revised Wisconsin DOT guidelines propose that a GEH of less than 5.0 be attained for at least 75% of intersection turn volumes.
- Current FHWA/Caltrans guidelines do not address the problem of unreleased vehicles. Unreleased vehicles present a serious calibration issue since they create a mismatch between the travel demand and actual number of vehicles that are successful in getting through a network. Improvements to networks featuring significant numbers of unreleased vehicles can lead to more vehicles traveling onto the network, and thus higher assessed vehicle-hours of delays and a perception of negative impacts while there can be in fact operational benefits. To avoid such a situation the number of unreleased vehicles should be kept to a minimum. While short-lived queues can be tolerated, there should be no unreleased vehicles left at the end of a simulation.
- It is important that vehicle fleets be adequately replicated to ensure proper calibration. This requirement applies more specifically to networks carrying heavy trucks, as these vehicles not only occupy more space than passenger cars but also have significantly different acceleration and deceleration behavior. Any network within which heavy trucks have a noticeable influence on traffic operations should include a separate modeling for these vehicles. In many cases, it may not be sufficient to simply indicate that a fixed proportion of all observed trips are made by trucks, as this can result in simulating truck trips between zones for which such traffic does not normally occur. Ideally, separate O-D flow matrices should be defined for trucks and any other relevant vehicle types.
- The adequate replication of travel patterns should be an important target, as multiple combination of trips can recreate observed traffic volumes on individual links. For

instance, freeway flows can be replicated through various combinations of short, medium, and long zonal trips. However, formal targets regarding the validation of route selection have yet to be developed. The current practice typically puts each modeling team in charge of ensuring the validity of travel patterns. Specific guidelines would help ensure consistency across models. The draft revised Wisconsin DOT guidelines suggest, for instance, to verify that 9 out of 10 routes followed by individual vehicles match routes typically that are followed in reality. The draft guidelines also suggest that there must be rare occurrences of vehicles exiting a freeway from a ramp and re-entering the freeway at the next ramp. While these targets are a step in the right direction, their application can be limited by the fact that actual observations of route patterns are rarely available. This limitation may thus restrict evaluations to high-level assessments based on subjective knowledge of local traffic behavior.

  - Existing calibration guidelines do not address transit components. While this was not an issue for most of the completed CSMPs, it can become so for future CSMPs if it is planned to put a greater emphasis on evaluating transit-related improvements. For instance, the need to accurately model transit elements has already pushed modelers for the FHWA's ICM program evaluations to develop calibration guidelines for light-rail station volumes and park-and-ride activities.
  - Networks offering multiple paths between O-D pairs will generally require more extensive calibration due to the need to calibrate route selection for all major combinations of origin and destination nodes.

- **Model review:**
  - The audit of simulation models can be a time-demanding process, particularly when the calibration proves difficult.
  - In a number of cases, the time required for the review has significantly exceeded what was initially expected. These longer-than-expected reviews identify a need to adjust perceptions and resource allocations pertaining to this critical modeling task.
  - Individuals tasked with reviewing simulation models did not always have full knowledge of the simulation tools being used. This created some difficulty in allowing each reviewer to conduct a full review of the submitted models.
  - While a standardized review process was promoted, this process was not applied equally in all Districts. Variations in the review process may have introduced variations in the quality and accuracy of the developed models.
  - Project teams often submitted for reviews models that were flawed and that lacked appropriate quality control. This not only increased the time required for the reviews, but also shifted to the reviewers the burden of identifying coding mistakes to be corrected, while this task should have been performed by the modeling team itself.
  - The review process was not always supported with adequate documentation. In some cases, needed corridor revisions or model approvals were based on simple verbal agreements. There should be proper documentation of all review findings and subsequent changes made to a simulation model, as well as of all approval and rejection decisions. This will not only help ensure transparency in the modeling process, but also help understand what difficulties may have been encountered, help ensure that valid

solutions were applied to each problem, and help identify whether improvements in the modeling and review processes are needed.

- No guidelines currently exist on when to recommend the termination of a modeling project that is not achieving its goal. While such an outcome is rare, and generally not desired, some CSMP modeling efforts have unsuccessfully extended across multiple years due to calibration difficulties. This includes one modeling project that has extended over 4.5 years. Projects extending beyond two years carry a certain risk of losing stakeholder interest and being affected by staff turnover. To address such a situation, guidelines should be developed to help review teams and project managers determine whether it is worth pursuing an effort that is continuing to experience significant difficulties.
- Involving Caltrans individuals familiar with the network being evaluated early and continuously in a modeling project can improve the quality of the work and save both resources and time.

- **Model application:**
  - A variety of approaches were considered to determine the number of simulation runs to execute. While some modeling teams relied on statistical formulas to assess the number of runs required to achieve certain accuracy, some task orders arbitrarily imposed an exact or minimum number of runs. Some consultants further determined the number of runs based on prior experiences. Ideally, the number should be based on the specific needs of each evaluation project and the observed variability of simulation results across individual runs.
  - While statistical formulas can determine an exact number of runs to execute, these formulas will often suggest a large number, such as 30, 40 or 60 runs per scenario. This can potentially lead to very long studies. Experience suggests that only marginal gains in accuracy are often achieved past a certain number of runs. A more practical approach can be to execute only as many runs as necessary to achieve a reasonably accurate representation of the average traffic conditions within the network based on the variability of simulation results across runs.

- **Evaluation of scenarios:**
  - The absence of formal guidance on how to evaluate corridors resulted in some project teams compiling performance measures using segments defined by observed bottlenecks and others considering segments based on major interchanges.
  - A clear link was not always established between the desired corridor management objectives and selected performance measures. As a result, performance ranking and project prioritization were frequently solely based on operational benefits (for instance, solely based on delay reductions) that may not have adequately reflected other corridor management objectives.

- **Project reporting:**
  - The lack of reporting standards made it difficult to compare modeling and calibration results across various corridors. There were not only variations in how the information was presented but also in what was documented. Some modeling teams provided

relatively thorough descriptions of modeling activities, while others presented only summary descriptions.

- **Model Maintenance**
  - Significant staff turnover has been observed at many of the consulting firms that have worked on the development of CSMP simulation models. While many of the observed changes occurred after the conclusion of a simulation study, the departure of staff responsible for the development of a model has resulted in a loss of knowledge on how the model was developed and what assumptions were made, particularly in cases in which these elements were not thoroughly documented.
  - Not all Caltrans Districts appear to have in place a formal plan for the maintenance of developed CSMP simulation models. At issue is how to ensure that the developed models retain their usefulness following the completion of the project that has led to their development. While there is evidence that some models have been used beyond their initial CSMP scope, there are only a few examples. If no actions are taken to periodically bring a model up-to-date, interest in using it will gradually decrease. This can ultimately lead to the decision to develop an entirely new model for conducting future evaluations along the same corridor and thus, in the continuing perception that simulation modeling is typically a single-project endeavor.
  - A formal simulation model maintenance plan should identify when model updates are to be made and by whom. The plan should also indicate how changes in network geometry and traffic demand will be tracked, particularly if model modifications are only periodically done.
  - Recalibration of a simulation model is required each time a new version of the simulation software implements changes in the underlying driver behavior model. Recalibration is typically not required for minor revisions that do not affect the simulation engine, such as revisions implementing new coding or data analysis tools.
  - Model recalibration is required following major changes to the road geometry or travel demand. Recalibration can also be required following changes made to the modeled road network to correct coding errors.
  - In certain situations it could be determined that a model that had been developed with a previous software version can be used without having to port it to a new version. This can be true for models that have been developed relatively recently. However, the opportunity should always be taken to port a model to a new version each time a recalibration is needed.

10. RECOMMENDATIONS

While traffic simulation models have been found to have positively impacted the evaluation and prioritization of improvements for CSMP corridors, several aspects regarding their development, calibration and application would benefit from improvements in future CSMP operational evaluations. The following are key recommended improvements:

- **Setting up expectations:**
  - Project stakeholders should agree on the scope and objectives of a modeling effort prior to initiating model development. Scoping discussions should take into consideration the expectations from various stakeholders, the required tasks, and the limitations that can be imposed by available simulation tools. A clear understanding of how the selected simulation tool is to be used to support engineering decisions should also be developed.
  - Project managers and decision-makers should be adequately informed of the needs, limitations and risks associated with using simulation to evaluate long corridors. Such knowledge would help ensure that individuals affecting project decisions would not buy in on overly optimistic promises from model developers or put too much faith on the capability of a particular tool.

- **Selection of modeling approach and modeling tool:**
  - Various elements should be considered when selecting whether to conduct evaluations using a microscopic, mesoscopic, macroscopic, or hybrid approach, and which simulation software to use. Key considerations include:
    - Ability to model improvements of interest with built-in functions, custom functions developed through an Application Programming Interface (API) or third-party expansion plug-in modules.
    - Availability of data required for modeling and calibration.
    - Ability to produce vehicle emission estimates.
    - Simulation runtime.
    - Agency expertise with simulation tool.
    - Training needs to enable agency staff to use the simulation tool.
    - Past success stories in utilizing the simulation tool for evaluating corridors.
    - Popularity of modeling tool among other agencies/consultants within the area.
    - Availability of previously developed models covering the corridor.
    - Ability to migrate developed models across software versions.
    - Diverging jurisdictional preferences.
  - While microscopic models have often been perceived as ideal evaluation tools due to their ability to simulate the movements of individual vehicles, there are situations where a simplified modeling approach is better suited:
    - **Long range evaluations (beyond 10 years)** – Given the high level of uncertainty associated with long-range forecasts, it is often more efficient to conduct evaluations targeting a horizon far into the future using available travel demand models or macroscopic simulators. Some modeling teams who tried to use microsimulation for long-range evaluations also faced difficulties in handling the oversaturated conditions that often resulted from high expected traffic growth.

      - **Evaluation of large networks** – Developing large microscopic road networks can involve complex and time-consuming calibration, in addition to leading to slower run speeds. While macroscopic models allow large networks to be simulated quickly, they may not adequately replicate the full range of operational conditions observed on freeways or arterials. Conceptually, the most promising approach for simulating large networks may be to use a hybrid microscopic/mesoscopic model. However, as indicated below, there is still uncertainty regarding the fidelity of these emerging models.
      - **Evaluation of route diversion effects** – While many microscopic simulators offer dynamic routing capabilities, there is still uncertainty regarding their ability to accurately reproduce route selection behavior in networks featuring multiple paths. Available macroscopic models do not generally model this behavior adequately. Currently, the most frequent approach for assessing route diversion effects is to employ mesoscopic simulators specifically designed to assess traffic demand effects (e.g., DynaMIT, Dynasmart, and DynusT). Dynamic route selection across large networks is also available with the TransModeler and AIMSUN hybrid microscopic/mesoscopic modeling options. However, the validity of route selection within these models still needs to be evaluated.
      - **Evaluation of mode shifts** – Current microscopic simulators are not designed to handle mode shifts effects. Such effects are typically evaluated using travel demand models or mesoscopic traffic simulators specifically designed to assess traffic demand effects.
   - Prior to selecting a macroscopic simulation tool, the tool must be thoroughly evaluated to assess whether it can adequately account for behavioral changes that may result from the operational improvements being investigated. The ability to adequately replicate observed behaviors should also be verified. Examples of key behaviors that should be verified include off-ramp queues propagating onto the freeway mainline, the operational influences between HOV and non-HOV traffic, and the operational impacts of buses and commercial vehicles on general traffic. If the available macroscopic models cannot suitably replicate key behaviors, the evaluation team should instead seek to use a microscopic or mesoscopic model.
   - While emerging hybrid microscopic/mesoscopic modeling capabilities offer the potential of simulating large networks with fast execution speeds, there is still uncertainty whether this approach significantly simplifies data collection and/or network modeling. Furthermore, current hybrid models (e.g., TransModeler, and AIMSUN) have yet to be fully vetted, particularly their ability to correctly replicate traffic behavior at the microscopic/mesoscopic boundaries and to adequately assign routes across areas modeled with different fidelity.

- **Modeling scope:**
   - A bottleneck causality analysis should be completed prior to the completion of model scoping to ensure that the real causes of congestion are simulated, as well as to provide better stakeholder buy-in to the model calibration.
   - General evaluation scenario concepts should be developed by the modeling team in collaboration with project stakeholders prior to finalizing the boundaries of a corridor.

- Task orders should clearly indicate that the modeling of peak periods is to include shoulder hours. Ignoring these periods can affect the evaluation of improvements yielding benefits primarily when congestion is building or dissipating.
- Guidelines should be developed to determine an acceptable temporal analysis scope for microscopic and mesoscopic models. Use of microscopic simulation can be justified for evaluating corridor improvements within a 10-year horizon. However, the high level of uncertainty associated with long-term demand projections may not justify expending significant resources towards the development and calibration of microscopic models for evaluations beyond 10 years. For long-term evaluations, relying on an existing travel demand model will in many cases be a more cost-efficient alternative. Macroscopic models can also provide a viable alternative in such cases.
- Guidelines should be developed to determine when and where it may be beneficial to break up a long corridor into smaller sections that can be modeled separately.

- **Data collection:**
  - A detailed data collection plan indicating what is to be collected, from which sources, and for what purpose, should be developed by the modeling team and submitted for approval by Caltrans prior to initiating model development. The plan should not only cover efforts listed in the task order but also any additional efforts deemed necessary to support the modeling.
  - To aid with the development of an effective data collection plan, cooperation with Caltrans and other stakeholders should be sought as early as possible.
  - The data collection plan should distinguish what data is to be collected for model development and for model validation. Ideally, separate datasets should be used for both activities to avoid biases when conducting the model validation.
  - Modeling teams perceiving that insufficient budget or time is allocated to the data collection effort should inform Caltrans in writing of the risks potentially introduced by this situation. A potential recommendation to address the problem should also be provided.
  - To minimize the use of poor data in model development or calibration, all modeling teams should be required to validate the data they collect, as well as the data that are provided to them for which there has been no prior validation. For instance, checks should be made to ensure that the PeMS data provided to the modeling team does not contain an excessive proportion of inputted data or that the average travel time estimates were derived from a suitable number of observations.
  - All data validity checks should be documented in writing. This includes documenting the validation processes followed, the problems found, and the solutions that were applied to resolve the problems. While this may be viewed as an additional burden, documenting these activities may help explain unexpected problems or identify potential remedies at a later modeling stage.
  - Maps should be used to summarize the data elements that will be or have been collected. While tables often appear to be a less time-consuming approach from the modeling team's perspective, tables often present information in a way that is more difficult to assess from the reviewers' standpoint.

- Methodologies for determining appropriate data sample sizes should be investigated. In many modeling efforts, average travel times were determined based on two or three days of observations. While this approach is appropriate in some cases, it is not necessarily valid in corridors with significant variability in traffic conditions.
- Current detection coverage and detector maintenance practice should be re-evaluated to assess whether they adequately support simulation model development and maintenance. For instance, a higher maintenance priority may be assigned to detectors providing key inputs to simulation models. Identified detection gaps should also be addressed as soon as possible.
- The benefits of developing a centralized and standardized data warehouse responsible for gathering, collecting, processing, and storing data should be explored. With the exception of PeMS, multiple functional units within Caltrans are currently responsible for gathering, collecting and processing the data required for simulation studies (for instance, congestion data, accident data, intersection turning counts, managed lane operational reports, etc.)

- **Travel demand modeling:**
    - Wherever travel demand models are used as information sources, active participation should be sought from individuals responsible for the development and/or use of these models.
    - Guidelines should be developed to ensure that modeling teams perform adequate checks on the reasonableness of the traffic patterns that are obtained from travel demand models or developed from traffic counts using O-D matrix estimation (ODME) techniques.

- **Model calibration:**
    - The current set of calibration standards should be reviewed to address identified gaps. Elements that may be in need of revision include:
        - Calibration of bottlenecks (for instance, providing quantifiable flow and speed targets for bottlenecks, requiring higher flow and GEH compliance levels on links defined to be part of a bottleneck);
        - Calibration targets for HOV lanes (to account for the lower volumes often observed on these lanes);
        - Calibration of turn movements at intersections;
        - Validation of route selection;
        - Calibration of transit elements;
        - Application of calibration targets to simulation periods (for instance, application to each hour rather than the entire evaluation period);
        - Presence of unreleased vehicles at network entry points; and
        - Usability of limited data samples in calibration activities.
    - A committee composed of staff from Caltrans, staff from other state DOTs, and representatives from consulting firms should be formed to assess issues regarding model calibration and provide recommendations on calibration standards.

- **Model review:**
  - To ensure consistency, a uniform review process should be applied across all Districts. This process should include uniform checklists and comment/review forms.
  - Peer-reviewers should be given more than two weeks to conduct detailed reviews.
  - All model approvals and rejections should be documented, including the rationale for rejecting or approving a model for which issues remain.
  - Initial model review should consist of a two-step process. A first review would focus on verifying that a model does not contain gross coding errors. Once a model has passed this step, a second review would then assess its ability to replicate observed traffic.
  - Reviewed models exhibiting a high number of simple mistakes should be immediately returned to the modeling team for revisions before continuing with the review.
  - Plots showing the stability of simulation results across runs with different random number seeds should be part of the calibration documents submitted for review.
  - The evaluation of scenarios should not be allowed to start until the calibration report and calibrated model have been officially approved. Similarly, all scenarios should be developed from the approved calibrated model, not an intermediate model.
  - Individuals tasked with technical model reviews should have a basic knowledge of the traffic simulation software being used. They should know how to open a network, initiate a simulation run, and utilize the various audit tools available.
  - Individuals tasked with detailed calibration review should have a working knowledge of the traffic simulation software, as well as a general understanding of simulation modeling, traffic engineering, and traffic operation principles. While individuals without adequate experience can spot obvious glitches, such as whether a model appears to adequately replicate bottlenecks, they may lack the technical knowledge to uncover more subtle problems that can affect simulation results.
  - Training on how to conduct a simulation model review should be offered to individuals participating in a modeling/evaluation project.
  - Guidelines should be developed to determine when it may be in the best interest of Caltrans to terminate a modeling project facing continuous difficulties.

- **Model application:**
  - A consistent standard should be developed for determining the number of simulation runs to execute. While some task orders allowed the modeling team to determine the number of runs, others imposed a fixed or minimum number. This provided a somewhat inconsistent evaluation standard.
  - All modeling teams should provide a justification for the number of simulation runs that are to be executed to evaluate each scenario. This justification should be based on an analysis of the variability of simulation results across individual runs, not simply on prior modeling experience.
  - A strict application of statistical formulas to determine the number of runs to execute based on the variability of simulation results is not formally recommended as these

formulas will often lead to an impractically high number. Execution of a smaller number of runs is acceptable if this number is deemed sufficient to produce adequate averages.

- The number of runs to execute should ideally be assessed against the variability of all critical performance measures considered. The number of runs to select should then correspond to the highest number returned by the individual assessments.
- Evaluations based on a single simulation run should not be allowed for any stochastic-based simulation model, such as Paramics, VISSIM, AIMSUN and TransModeler.

- **Evaluation of scenarios:**
  - All performance measures should be linked to specific corridor management objectives.
  - The relative importance of each performance measure should be determined, and agreed upon, by all project stakeholders.
  - Task orders should provide clear instructions regarding corridor segmentation. Ideally, the segmentation should be based on major bottleneck and interchanges and not result in the definition of segments less than 2 miles in length.
  - A formal cost/benefit analysis should be conducted for all CSMP operational evaluations. Where appropriate and justifiable, a cost-effectiveness analysis can be conducted instead.
  - Unless justification for another evaluation methodology is provided, the Cal B/C model is recommended for conducting cost/benefit evaluations since this model was specifically developed by Caltrans for evaluating transportation projects.
  - To help compare alternative scenarios, all evaluation reports should provide in a graphical format a summary of the benefits, costs, and cost effectiveness metric for each evaluated alternative. Figure 67, presented in Section 5.14.16, illustrates how such information might be presented.
- **Project reporting:**
  - Templates outlining what needs to be described regarding data collection and processing, model development and calibration, and scenario development and evaluation should be developed to standardize project reporting. The objective is not only to ensure that modeling activities are adequately described for archival purposes, but also to ensure that adequate modeling information is passed down to individuals who may be tasked with future model maintenance and utilization.

- **Maintenance and utilization of developed models:**
  - Caltrans should develop a formal plan for maintaining simulation models up-to-date and for promoting their use in support of agency-sponsored projects. Current practice within some Districts can be used as a starting point. The plan should identify which Division would be responsible for storing the model files, the supporting data, and the modeling reports; how frequently a model should be updated when not actively used; and who would be responsible for updating the model.
  - Caltrans should promote internally the availability of developed simulation models to support evaluations conducted outside the scope of CSMPs.

- **Staffing/professional capability needs:**
  - Caltrans should explore the possibility of maintaining in-house a core group of individuals with adequate simulation expertise who can be called upon to support or supervise modeling activities conducted by District staff or external consultants. In-house staff may include individuals based at Caltrans Headquarters in Sacramento and individuals with knowledge of local networks strategically based in key Caltrans Districts. An example may be to look at the current Computer Assisted Design (CAD) Unit.
  - To assist with staffing needs, Caltrans should track the resources expended (person-hours) to oversee simulation work, provide modeling assistance, conduct model reviews, and perform simulation work in-house.
- **Facilitating future corridor evaluations:**
  - Caltrans Districts should evaluate the possibility of developing a simulation modeling program aimed at maintaining simulation models in a ready-to-use state for key regional transportation corridors. Corridors targeted by this initiative would be those with frequent evaluation needs. The objective behind such a program would be to reduce the amount of time required to conduct simulation evaluations by ensuring that an up-to-date model is always available for use.

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11. CONCLUSIONS

Corridor System Management Plans (CSMPs) have been completed for 45 freeway corridors across California. A first objective of each CSMP was to understand how a corridor operates and why it operates that way. A subsequent objective was to identify effective packages of improvements that would benefit future corridor operations. For 31 of the 45 corridors, operational evaluations were conducted with the help of commercial microscopic, macroscopic or hybrid microscopic/mesoscopic traffic simulation models. This effort was the largest application of traffic simulation models to evaluate long freeway corridors within the United States.

While significant resources were expended on the development and calibration of simulation models, particularly for microscopic and hybrid microscopic/mesoscopic models, the benefits that were obtained from these models were generally found to outweigh their development costs. A majority of modelers, project managers and decision-makers who were contacted during this evaluation project indicated that the developed simulation models both met their initial expectations and fulfilled their intended role. The following are key benefits that were assessed to be obtained from the use of simulation models to evaluate corridor performance and proposed improvement scenarios:

- Simulation models helped quantify the impacts of various corridor improvements while accounting for complex interactions between road geometry, driver behavior, traffic control devices, and traffic management strategies.
- The ability to quantify the potential impacts on corridor operations facilitated the prioritization of improvements providing high net benefits or benefit/cost ratios.
- Many individuals indicated that it would have been far more difficult, if not impossible, to conduct similar corridor-based operational evaluations using deterministic analysis tools, and in some cases, even macroscopic simulation models.
- While simulation models did not always offer built-in modeling capabilities enabling the evaluation of all desired improvements, many microscopic models offered Application Programming Interfaces (APIs) allowing the development of custom functionalities filling these gaps. Such versatility typically does not exist with analytical tools and macroscopic models.
- Several individuals commented on the fact that results from simulations have strongly influenced investment decisions within the corridors being evaluated.
- Several project managers commented on the effectiveness of using visual animations extracted from microscopic simulation models to help decision-makers visualize the benefits provided by specific improvements, as well as issues associated with some proposed changes.
- The ability to visualize traffic behavior provided traffic engineers participating in the corridor evaluations with a powerful tool to analyze traffic operations under alternative situations and to identify the potential causes of observed operational problems.

The following are additional benefits that were derived from activities surrounding the development of simulation models:

- The simulation-based CSMP operational evaluations provided an environment in which professionals from various areas have been able to work closely and exchange information. In turn, this environment facilitated the building of knowledge, technical skills, managerial skills and professional expertise on how to effectively use of traffic simulation as an operational evaluation tool for freeway corridors.

- While modeling challenges were at times encountered, the dialogues that developed around these challenges often led to an understanding of the desirability of specific improvements or to the identification of new potential improvements. In some cases, the discussions surrounding the development and utilization of simulation models also led to improved decision-making partnerships among stakeholders.

The ability to further utilize the developed simulation models to support non-CSMP evaluations is another important benefit that has been derived from the CSMP modeling efforts. For instance, the availability of calibrated models covering many key urban freeway corridors can entice Caltrans staff to utilize the available models to conduct project evaluations that would have been cost-prohibitive to consider if the evaluation would have required the development of a new simulation model. While the existing models may need some adjustments or recalibration before being reused, particularly for those that are a few years old, these modifications should carry a lower cost than if a new model needs to be developed from scratch. In particular, adjustments made during repeated uses can allow a model to be periodically updated to current conditions and thus to remain in a ready-to-use state.

Although some of the modeling efforts required more time than expected due to calibration difficulties, many of the encountered problems were associated with the novelty of the scale of the modeling effort. While simulation tools have been used in the past to evaluate freeway or arterial improvements these efforts have generally focused on much shorter or less complex corridors. It is therefore to be anticipated that lessons learned from the current modeling efforts will allow future evaluations to experience fewer difficulties, enabling them to be completed in shorter time and with fewer resources, provided that there is no significant change in modeling scope. Potential evidence supporting this conclusion is the recent completion of the CSMP for the I-5 corridor in Orange County using the Paramics microscopic simulation model. This simulation study took slightly less than 12 months to be completed, as opposed to an average of 35 months for earlier CSMP modeling efforts, and for a smaller overall cost.

Based on the demonstrated benefits, it is strongly recommended that traffic simulation tools continue to be used to support CSMP operational evaluations. While a general preference is to keep using microscopic models, macroscopic models can also be used to reduce evaluation costs and time where such models are deemed adequate. On the use of hybrid microscopic/mesoscopic models, there is not yet enough evidence to provide a recommendation on their utilization for evaluating corridor operations. Regardless of the model used, the implementation of the various recommendations outlined in this report should further strengthen how traffic simulators are used to conduct evaluations by promoting more standardized, transparent and accountable practices.

Ideally, a program supporting the development and maintenance of simulation models within individual Districts should be developed. To accomplish such a goal, Caltrans will need to develop a formal policy on the use of simulation to support both CSMP and non-CSMP evaluations, and to have in place appropriate funding mechanisms to support modeling efforts, particularly efforts anticipated to last more than one year since such projects will require fund commitments over more than one fiscal year.

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APPENDIX A – CORRIDOR SIMULATIONS OUTSIDE CSMP/ICM SCOPE

This appendix summarizes the result of a scan of professional literature that was conducted to assess the extent of utilization of traffic simulation models, particularly microscopic and mesoscopic models, to evaluate the performance of transportation corridors or large road networks. A particular focus of this scan was to identify projects that recently completed and that attempted to model substantial freeway corridors, freeway systems or road networks. The scan was also restricted to projects using commercial traffic simulation software and projects and excluded projects that were mainly academic in nature.

Information about each project was collected based on published reports, information obtained through the project's survey, and personal contacts with individuals involved in some of the modeling efforts. A particularly difficult aspect of the scan was a general lack of documentation regarding the identified individual projects. Since many of the modeling projects were executed for practical purposes, detailed modeling reports were not typically produced for an outside audience. It was also beyond the scope of the current project to conduct a detailed review of the various modeling projects identified.

The following subsections provide summary information about the various projects that were identified within the following categories:

- Modeled corridors within California;
- Modeled corridors outside California but within the United States and Canada; and
- Modeled corridors in Europe and Asia.

MODELING PROJECTS WITHIN CALIFORNIA

Notable simulation projects that have been conducted within California outside the scope of the CMPS evaluations include the following:

- **I-680 Corridor** (Gardes *et al*. 2001; Cambridge Systematics and System Metrics Group, 2002) – This project, executed in the early 2000s, modeled in Paramics a 19-mile section of southbound I-680 on the east side of the San Francisco Bay, from the I-580 interchange in Pleasanton to the SR-237 interchange in Milpitas. This model was used to evaluate the potential impacts and benefits resulting from the deployment of the traffic management strategies. Strategies that were evaluated include the implementation of ramp metering, addition of auxiliary lanes at various locations, and addition of an HOV lane along the freeway. Experiences from this project were eventually used to develop a blueprint for the execution of CSMPs.

- **Greater Eureka Microsimulation Model** (Caliper, 2012) – Caliper completed in 2010 the development of a microscopic TransModeler model of the Greater Eureka area (see Figure A.1). This project was funded by the Humboldt County Association of Governments and Caltrans, and used by Caliper to demonstrate the capabilities of TransModeler. The resulting model includes all streets within a 16 square mile area, as well as major roads extending outside the city. Bus services and bicycle lanes are also modeled. Traffic movements within the network are further modeled using 400 O-D traffic zones, 15-minute O-D flow tables and dynamic traffic assignment algorithms. Since its completion, this model has been used to evaluate the feasibility of roadway and access management strategies along US-101.

Figure A.1 – Eureka TransModeler Model
(Source: Caliper corporate website)

- **Sacramento DaySim/TRANSIMS Integrated Model** (RSG Inc., 2010) – Research System Group completed in 2010 the development of regional travel demand model for the Sacramento area integrating the DaySim activity-based travel demand model with the TRANSIMS microscopic simulator. The model network includes 6800 links, 4500 nodes and 22,000 activity locations. The developed simulation framework implements an iterative process in which travel itineraries produced by DaySim are transferred into TRANSIMS for microscopic network performance evaluation and network performance data produced by TRANSIMS sent back to DaySim for updating trip and travel itineraries forecasts. The process repeats until convergence is reached. Due to the high level of disaggregation in trip forecasting and size of the road network modeled, run times of up to 80 hours were reported for the Sacramento model.

MODELING PROJECTS WITHIN NORTH AMERICA

Notable recent applications of traffic simulation models within the United States or Canada to evaluate the performance or support the operation of transportation corridors or large road networks located include the following:

- **I-94 Corridor, Wisconsin** (Hourdos and Michalopoulos, 2008) **–** Paramics was used to model a 40-mile section of I-94, from the Illinois border to Milwaukee, along with two alternative routes, to study the impacts of growth along the corridor. The cost of this project was reported to be between $300,000 and $400,000. A reported issue was the need to develop the O-D flow matrix entirely from traffic flow counts using Paramics tools since the caretaker of the regional planning model did not cooperate with the modeling team.

- **Milwaukee Freeway Network** (T-Concept, 2012) – T-Concept completed in 2006 a 3-year project seeking to model the Milwaukee freeway system as part of the Freeway Systems Operational Assessment project. Figure A.2 illustrates the geographic scope of the modeling, which extended over 150 miles of freeways and parallel arterials and included 40 system and service interchanges. Traffic demand was further modeled using a 100-zone system. This network was eventually used to support project scoping, evaluation and programming along the freeway network. The calibration targets that are currently being recommended by the FHWA and Caltrans for the development of microscopic simulation models were originally developed by the Wisconsin DOT for this freeway modeling project.

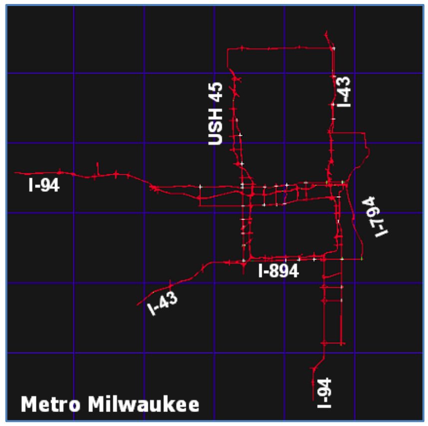

Figure A.2 – Paramics Model of Milwaukee's Freeway Network

- **I-75/I-96 Ambassador Bridge Gateway Maintenance of Traffic Simulation** (Quadstone Paramics, 2009a) **–** T-Concept completed in 2006 a large-scale Paramics modeling of the freeway network in the metropolitan Detroit area. The resulting modeling is shown in Figure A.3. The network was developed to evaluate the impacts of closures and development of mitigation measures related to the reconstruction of the I-75/I-96 Ambassador Bridge Gateway reconstruction, a heavily traveled crossing with Canada carrying a significant proportion of trucks. The model encompasses 25 miles of I-75, 18 miles of I-94 and 13 miles of I-96, as well as 100 miles of arterials. 440 zones were further coded to model traffic demand patterns within the network.

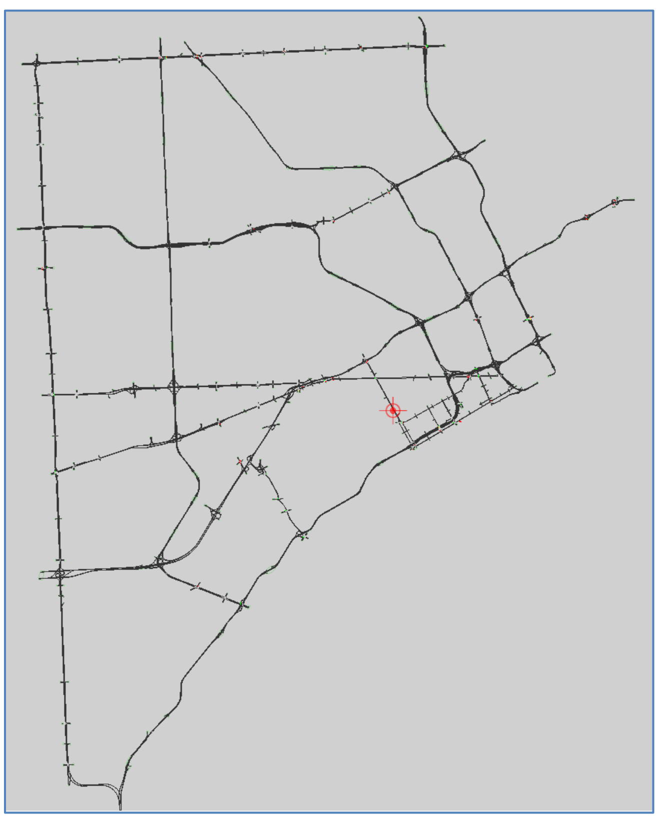

Figure A.3 – Paramics Model of Detroit's Freeway Network

- **US-41 / WIS-441 Corridor, Wisconsin** (Beuthling, 2009) **–** Paramics was used to model an 18-mile corridor covering the US-41 and Wis-441 freeways in Appleton, Wisconsin. The modeled freeway sections are shown in Figure A.4. This simulation model was specifically developed to help identify deficiencies along freeway mainline, ramps, and ramp intersections, forecast turning movements for 2020 and 2035 conditions, and develop short-term improvements for the corridor.

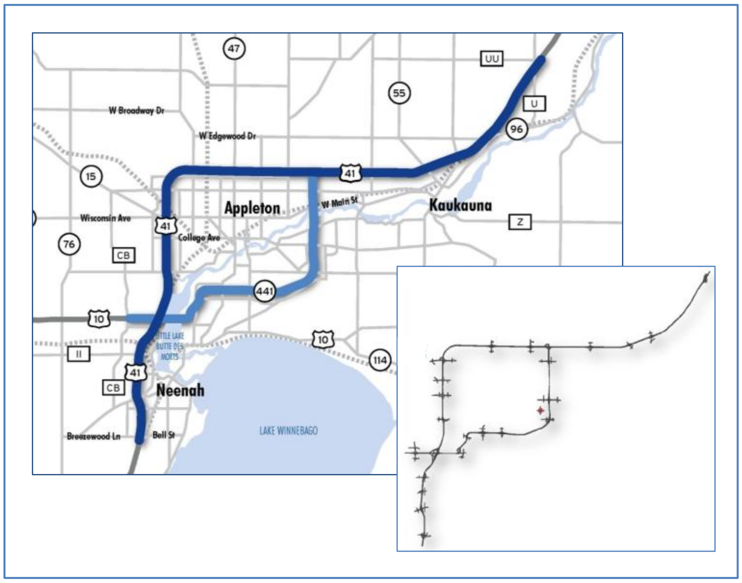

Figure A.4 – Paramics Model of US-41/WIS-441 Freeways in Wisconsin

- **Kansas City Core Network** (Hourdos and Michalopoulos, 2008) **–** HNTB Corporation used a VISUM/VISSIM combo to develop a simulation model for the downtown core area of Kansas City. An illustration of the modeled VISSIM network is shown in Figure A.5. Within this network, VISUM was used to estimate travel demand within the modeled area, while VISSIM provided a detailed microscopic simulation over the same area. After its development, this model was used by the City of Kansas City, the Missouri DOT, and the Kansas City Area Transportation Authority (KCATA) to assess the impacts of one-way street conversions, street closures during construction, changes to the central business district freeway loop, changes to bus operations in the central business district, and impacts of special events.

Figure A.5 – VISSIM Model of Downtown Kansas City

- **Downtown Miami Transportation Master Plan** (Quadstone Paramics, 2009c) – Leftwitch Consulting Engineers modeled in Paramics 481 intersections in downtown Miami and travel options offered by various modes of transportation. Figure A.6 illustrates the extent of the coded road network modeled. This modeling is considered to be one of the largest applications of Paramics in the United States. The resulting network was used to analyze two-way to one-way street conversions, depressing the I-95 freeways to an at-grade/tunnel system, constructing the construction of a tunnel under the Miami River along the 1st Avenue, and the effects of adding light rail and people mover lines.

Figure A.6 – Extent of Paramics Modeling of Downtown Miami

- **Midtown Manhattan 11th Avenue Study** (Quadstone Paramics, 2009b) – Urbitrans coded in Paramics a sizable area of West Midtown Manhattan in New York City. A screenshot of the model is shown in Figure A.7. The model covers over 200 signalized intersections across a 200 block area stretching from 23rd Street to Central Park, and 6th Avenue to the Hudson River. This model was used to assess existing and future traffic conditions across the area, as well as the effects of road closures due to railroad rehabilitation work on viaducts in the area.

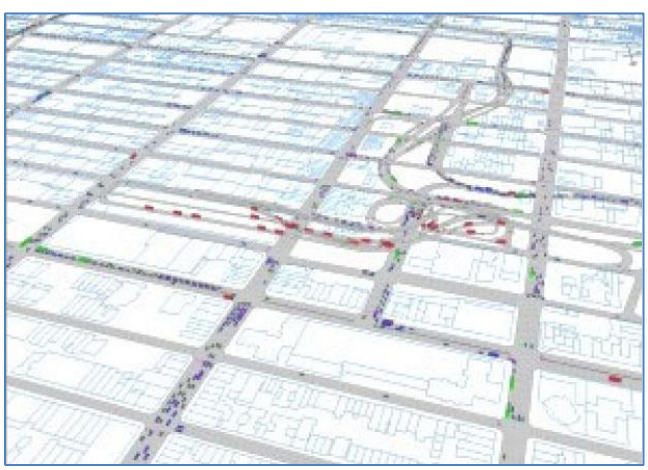

Figure A.7 –Paramics Model of Midtown Manhattan 11th Avenue Study

- **Manhattan Traffic Model** (Papayannoulis and Torday, 2011) – In 2009, the New York City Department of Transportation, in collaboration with Cambridge Systematics, STV and TSS, initiated the development of a large-scale AIMSUN modeling of Manhattan and its immediate peripheral arterials. The model simulates microscopically the vehicular and pedestrian traffic between 31th Street and 37th Street. Traffic between 14th Street and 66th Street was further modeled using a detailed mesoscopic approach, while traffic in surrounding areas from the tip of Manhattan up to 179th Street was modeled with a less detailed mesoscopic approach. The entire model covers over 2,800 miles of lanes and includes 1583 centroids or zones. When completed, the resulting model will be made available to address the cumulative network impacts of construction projects, roadway closures and traffic operations plans, as well as to provide a point of departure for future work. The extent of the modeling is shown in Figure A.8

Figure A.8 –AIMSUN Microscopic/Mesoscopic Modeling of Manhattan

- **Columbus, Ohio** (Hourdos and Michalopoulos, 2008) **–** In anticipation of significant population and employment growth, a VISUM/VISSIM modeling of the Columbia metropolitan area was completed in 2005 to investigate access to the downtown area during the AM peak period. Figure A.9 shows the 30 square-mile area covered by the model. The downtown area was modeled microscopically using VISSIM, while the surrounding areas were modeled macroscopically using VISUM. The resulting network included 25 freeway interchanges, 330 signalized intersections, 120 unsignalized intersections, and all public transit lines within the area. The VISSIM model was calibrated using data collected from detectors, extensive manual counts, and floating car studies. New calibration methodologies were also apparently developed.

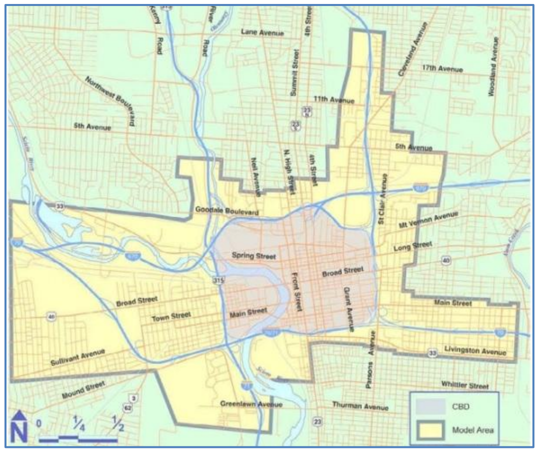

Figure A.9 – Geographical Scope of VISUM/VISSIM model of Columbus, Ohio

MODELING PROJECTS IN EUROPE AND ASIA

Examples of modeling efforts from outside North America conducted to evaluate the performance or support the operation of transportation corridors or road networks include the following:

- **Hessian Freeway Network, Germany** (Hourdos and Michalopoulos, 2008) – The Road and Traffic Authority of the Federal State of Hessen and the City of Frankfurt in Germany completed in 2003 the development of an AIMSUN model covering the regional freeway network. An illustration of the modeled network is shown in Figure A.10. This model was built to support decision-making activities within a traffic management system designed to convey real-time traffic information to drivers within the freeway network and implement real-time traffic management strategies in response to incidents and specific events. It covered 940 miles of freeways, 200 signalized intersections, and 262 unsignalized intersections across a network of 245 O-D zones. The success of this project eventually led TSS to develop the AIMSUN Online traffic management tool.

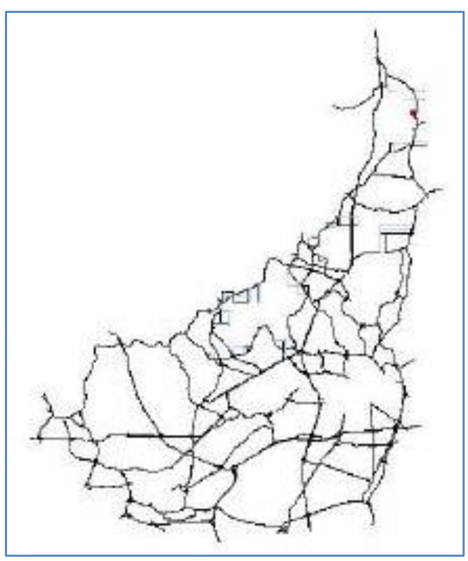

Figure A.10 – AIMSUN Model of the Hessian Freeway Network in Germany

- **Barcelona, Spain** (Hourdos and Michalopoulos, 2008) - Barcelona's Agencia de Ecologia Urbana completed in 2002 an AIMSUN mesoscopic/microscopic model of the Barcelona road network for the purpose of using it as a master model to support operational planning projects in various districts across the city. The resulting model is shown in Figure A.11. The microscopic model at the core of the modeled network includes 1563 roadway links, 659 intersections and 208 zones. The larger mesoscopic model surrounding the microscopic model encompasses 344 zones, 7,901 intersections, and 893 miles of roadway. A problem with the development of this network was an inappropriate traffic detection layout that did not allow proper O-D flow reconstruction.

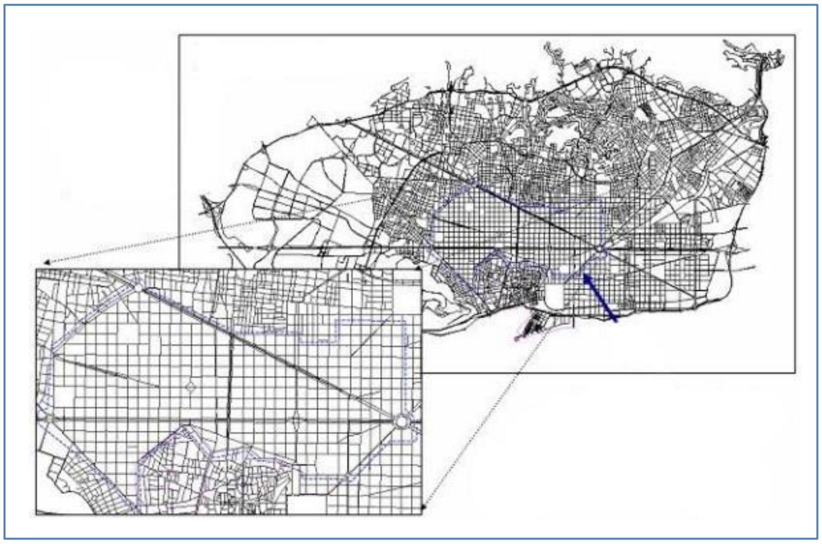

Figure A.11 –AIMSUN Model of Barcelona, Spain

- **Singapore City Center** (Hourdos and Michalopoulos, 2008) – AIMSUN was used to develop a large-scale mesoscopic model of the primary road network on the Island of Singapore. An illustration of the modeled network is shown in Figure A.12. This model was developed over 3 years. It covers an area of 425 square miles and models 2786 lane miles over 1025 miles of roads, 10,500 intersections and 3153 O-D zones. An interface with the SCATS real-time traffic signal control system was further developed to emulate the adaptive nature of the traffic signals operated within the city. This model is currently being used as part of the city's traffic management system to conduct off-line network analyses and real-time operational analyses for incident and congestion management.

Figure A.12 – AIMSUN Model of Singapore's Main Road Network

- **M-30 Ring Road, Madrid, Spain** (Torday, 2009) – Similar to the Singapore network, a mesoscopic AIMSUN model has been developed to support incident and traffic management along Madrid's M-30 Ring Road, a heavily congestion urban freeway carrying an average of 400,000 vehicles per day. Figure A.13 illustrates the area covered by the AIMSUN model. The model currently covers 352 miles of roadways and includes 3259 links and 1224 intersections.

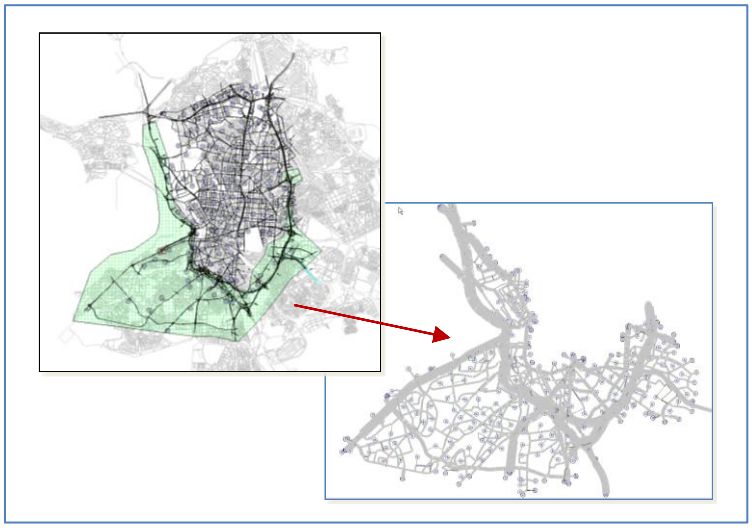

Figure A.13 – AIMSUN Model of M-30 Ring Road in Madrid, Spain

- **Munich North Metro, Germany** (Hourdos and Michalopoulos, 2008) – A model of the freeway network in the northern part of Munich was completed in 2003 using the VISUM/VISSIM combo. This model was developed as a test bed for the evaluation of en-route traveler information dissemination applications, dynamic speed control, and shoulder lane utilization. Figure A.14 presents a screenshot of the resulting network. It includes 6 freeway connectors, 23 interchanges, and 98 signalized intersections, in addition to featuring high congestion levels for a large portion of the day. Data from 98 traffic detector sites were further used to calibrate the VISSIM model. Its development required 18 person person-months, including 3 person person-months solely for identifying representative count profiles from a database of traffic counts and re-calibrating the O-D matrices.

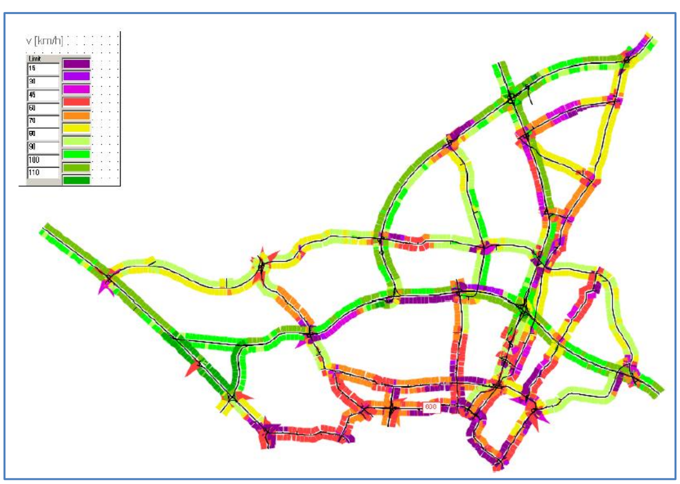

Figure A.14 – VISSIM Model of Munich's Freeway Network

- **Lausanne road network, Switzerland** (Hourdos and Michalopoulos, 2008) – AIMSUN was used to model Lausanne's primary road network. The geographical extent of the modeled network is illustrated in Figure A.15. It contains 4100 links, 1600 nodes and 290 zones. While it was initially developed to evaluate travel time estimation methods using probe vehicles, it has also been employed by the Lausanne City Council to evaluate various network improvement projects.

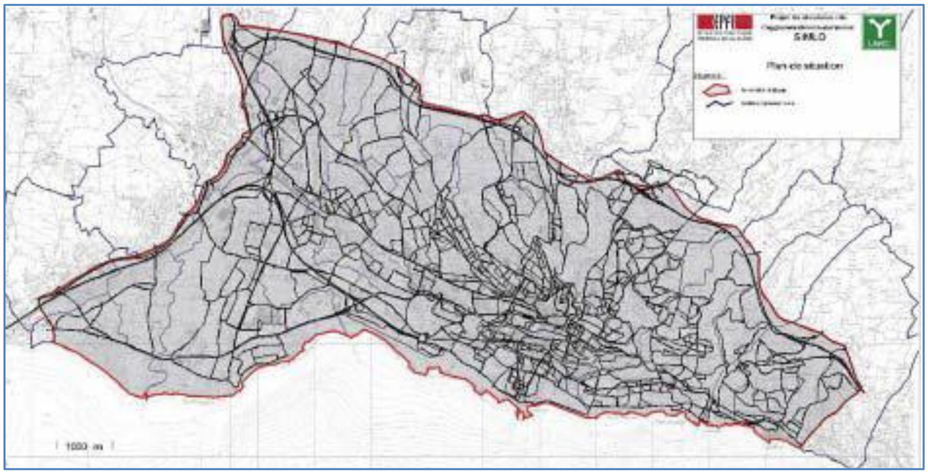

Figure A.15 – AIMSUN Modeling of Lausanne, Switzerland

- **Sydney, Australia** (Hourdos and Michalopoulos, 2008) – Several Paramics models were developed to cover various sections of the road network surrounding Sydney, Australia. Figure A.16 illustrates the three primary models developed. The Sydney CBD model covers an area of approximately 10 square miles and includes 2300 nodes, 5500 links, 300 signalized intersections and 270 O-D zones. Development of this network reportedly required more than 2000 man hours. An API module allowing Paramics to emulate the operation of the traffic signals using the SCATS real-time traffic signal control system was also used.

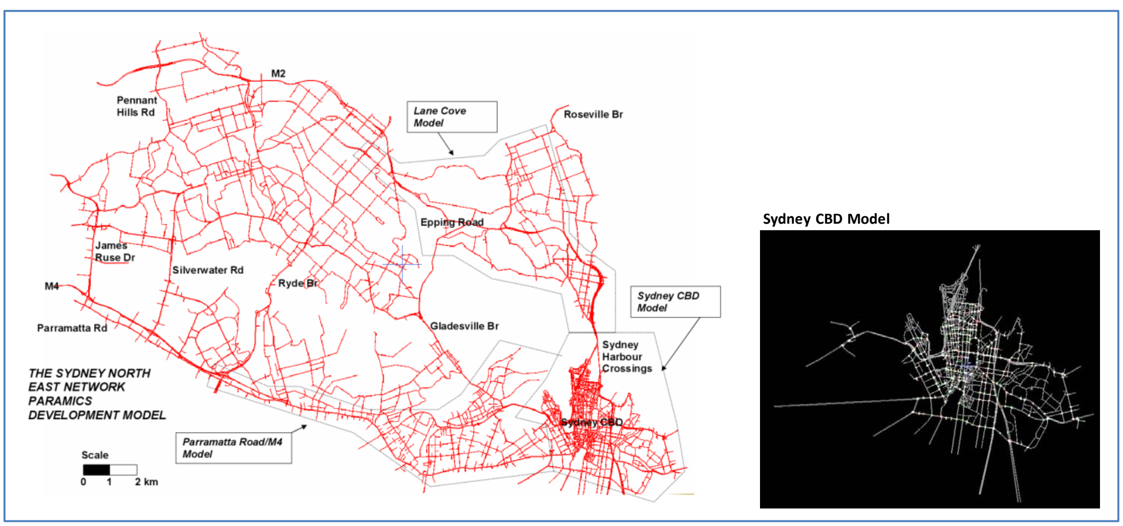

Figure A.16 – Paramics Modeling of Sydney, Australia

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