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Evaluation of Potential ITS Strategies Under Non-Recurrent Congestion Using Microscopic Simulation

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ABSTRACT

This report presents a micro-simulation method to evaluate potential ITS applications. Based on the commercial PARAMICS model, a capability-enhanced PARAMICS simulation environment has been developed through integrating a number of plug-in modules implemented with Application Programming Interfaces (API). This enhanced PARAMICS simulation can thus have capabilities to model not only the target traffic conditions and operations but also various potential ITS strategies. An evaluation study on the effectiveness of potential ITS strategies under the incident scenarios is conducted over a corridor network located at the city of Irvine, California. The potential ITS strategies include incident management, local adaptive ramp metering, coordinated ramp metering, traveler information systems, and the combination of above. Based on the calibrated simulation model, we implement and evaluate these scenarios. The evaluation results show that all ITS strategies have positive effects on the network performance. Because of the network topology (one major freeway with two parallel arterial streets), real-time traveler information system has the greatest benefits among all single ITS components. The combination of several ITS components, such as the corridor control and the combination scenarios, can generate better benefits.

1 INTRODUCTION

Many Intelligent Transportation Systems (ITS) technologies and strategies, such as vehicle actuated signals, ramp metering, and variable message signs (VMS) have been applied to the transportation systems and improving the real-world traffic condition. In the near future, some more complex ITS applications, such as adaptive signal control, adaptive ramp metering and their combination, have the potentials to be implemented in the real world. Field operational tests of these strategies may be difficult and costly; however, without prior testing, some ITS applications may not work properly, or positively impact traffic conditions (Pearce, 2000). For decision makers, questions related to whether an ITS strategy is warranted, which kind of strategy is suitable, the level of complexity to implement the strategy, and how to calibrate and optimize the operational parameters of the strategies, ought be investigated.

Microscopic traffic simulation is a software tool to model the real-world traffic system, including the road, drivers, and vehicles, in fine details. In a micro-simulation process, the state of an individual vehicle is continuously or discretely calculated and predicted based on vehicle-vehicle interactions. The car-following, lane-changing and gap-acceptance models are the basic elements of a microscopic traffic simulator. Notable instances of micro-simulators include PARAMICS, CORSIM, VISSIM, AIMSUN2, TRANSIM, and MITSIM (Yang et al., 1996, ITS, 1998, Jayakrishnan et al., 2000). With the advancement of computer technology and modeling traffic flow in the microscopic level, microscopic simulation is becoming a popular and effective tool for many applications, such as modeling and evaluating ITS, which are not amendable to study by other means.

As the first widely used micro-simulation software in the US, CORSIM was applied to the studies of signal control, transit, ramp metering and work zones, etc. (Lahiri et al., 2002, Tian et al., 2002). However, most of these studies were only restricted to a small network. The new generation of micro-simulators, including AIMSUN 2, PARAMICS and VISSIM, shows better capabilities on modeling over a large network. Current micro-simulation applications are mostly focused on calibration and validation issues, and studies under simple networks, either a fictitious network with assumed travel demands or a small-size real network. The following difficulties hinder the further application of micro-simulations (a) lacking of effective or practical OD estimation methods; (b) limited knowledge on network calibration; (c) inability to simulate the advanced algorithms when they are not available from the off-the-shelf model.

This research will make a simulation-based study on how potential ITS strategies can help solve the non-recurrent traffic congestion over a corridor network. These ITS strategies include incident management, local adaptive ramp metering and coordinated ramp metering, adaptive signal control, traveler information, and the combination of several ITS components. A capability-enhanced micro-simulation model, PARAMICS, will be used to model and quantitatively evaluate potential ITS strategies.

This report is organized as follows. Section 2 describes how to model and evaluate ITS in a micro-simulation environment through API programming. The procedure to evaluate an ITS application is presented. Section 3 provides the details how we calibrate the target corridor network in PARAMICS. Section 4 explains how we model the evaluated ITS strategies in PARAMICS simulation environment. The evaluation results are discussed in Section 5. Section 6 concludes the report.

2 EVALUATION METHODOLOGY

The purpose of the study is to use microscopic simulation as an evaluation tool to evaluate ITS. Massachusetts Institute of Technology has developed a traffic simulation laboratory, called MITSIMLab, to evaluate dynamic traffic management system. MITSIMLab consists of a micro-simulator for simulating the traffic network in details and a traffic management simulator for modeling operations of control devices. The MITSIMLab has been used for the evaluation of freeway control strategies (Jha, et al, 1999, Hasan, et al, 2002, Ben-Akiva, et al, 2003).

For us, we attempt to use a commercial micro-simulator to evaluate ITS. The selected simulator should have capabilities to simulate the current real-world traffic conditions and traffic operations, and model potential ITS strategies as well.

2.1 Micro-simulator: PARAMICS

PARAMICS (PARAllel MICroscopic Simulation) is selected to evaluate ITS strategies in this research. PARAMICS is a suite of microscopic simulation tools used to model the movement and behavior of individual vehicles on urban and highway road networks (Smith, et al, 1994). It offers very plausible detailed modeling for many components of the traffic system. Not only the characteristics of drivers, vehicles and the interactions between vehicles but also the network geometry can influence simulation results. PARAMICS is fit to ITS studies due to its high performance, scalability and the ability of modeling the emerging ITS infrastructures, such as loop detectors and VMS. In addition, PARAMICS provides users with API through which users can access the core models of the micro-simulator, and customize and extend many features of the underlying simulation model without having to deal with the underlying proprietary code. Though PARAMICS can model some simple ITS strategies, API programming is eventually required to implement more complicated ITS strategies.

2.2 Aspects of PARAMICS need to be complemented and enhanced

Each micro-simulator has its own features to simulate the real-world traffic. Specifically for PARAMICS, many aspects of PARAMICS need to be complemented and enhanced through API programming in order to better model ITS. In general, ITS involves the introduction of a variety of advanced technologies, such as information technologies, to the transportation system. Typical ITS applications include adaptive signal control, ramp metering, and dynamic route guidance, etc. One of their common features is that they need the real-time traffic information. For a complex ITS strategy, such as Changeable Message Sign (CMS) routing, not only drivers' routes but also traffic control facilities need to be controlled. As a result, an ITS strategy involves the connection with traffic information, routing behaviors, CMS, signal control, and ramp metering of the simulation. Our current efforts are limited to the following basic aspects of PARAMICS.

2.2.1 Path-based Routing

PARAMICS is a link-based simulator. Vehicles being simulated do not carry their whole routes but decide their route based on the routing table stored at each node along its route. These routing tables are pre-calculated based on the currently used traffic assignment method. A path-based routing mechanism is required for the applications of traveler information related ITS strategies, such as dynamic route guidance or CMS routing.

2.2.2 Real-time traffic information collection

The common feature of ITS is that ITS needs the real-time traffic information, generally collected by detectors or probe vehicles, for decision-making. PARAMICS can model loop detectors, the most frequently used sensors in the real world. However, aggregated loop data, which are generally provided by freeway systems and can be used for real-time traffic control, cannot be obtained directly from PARAMICS simulation. Also, the concept of probe vehicles needs PARAMICS to track a certain percentage of probe vehicles and extract travel time or travel speed information from them. This cannot be done without the involvement of API programming.

2.2.3 Actuated signal control

PARAMICS can basically model the fixed-time signal control. Besides, PARAMICS also provide a plan/phase language (i.e. a kind of script language) to simulate some simple actuated signal control logics. However, in the field, the widely used actuated signal controller uses the complex NEMA logic or type-170 logic. Our experiences found this script language is difficult to be used to model these complex control logics and to replicate these logics to multiple signalized intersections. The function of this API is equivalent to the local signal controller in the real world.

2.2.4 Ramp metering control

PARAMICS can model fixed-time ramp metering with multiple timing plans. However, a ramp-metering controller, developed in PARAMICS API, is required for the support of the development of adaptive ramp metering algorithms, which have more complicated control logics. The ramp-metering controller should provide interface functions that can be used for querying the old metering rate and setting a new metering rate based on the adaptive ramp metering algorithms. When the adaptive ramp-metering algorithm is not activated, the fixed-time metering will be the default control. The function of this API is equivalent to the local metering controller in the real world.

2.2.5 Database connection

PARAMICS does not have the capability to connect with a database. The advantage of the use of database is that database can become the medium where API modules can exchange data with outside programs or applications.

2.2.6 Performance measure

PARAMICS has strong abilities on the collection of statistics data. Except some general performance data, PARAMICS can output link-based, trip-based, intersection-based, and detector-based data. However, the current difficulties are

- With the increase of the size of the network, the number of links, trips, intersections, and detectors increases drastically in PARAMICS.
- Large amount of data are required to be processed after simulation runs in order to obtain the expected performance measures.
- Some performance measures, such as on-ramp waiting time, cannot be extracted from output measurement data.
- PARAMICS has a restriction on the number of output files to be opened during simulation under WINDOWS version.

The use of API to collect performance measures can obtain more performance measures directly and can decrease the amount of data post-processing works effectively.

2.3 Capability enhancements

2.3.1 Framework of the enhanced PARAMICS

The above capability enhancements are focused on the basic aspects of the micro-simulator, PARAMICS. Each of these basic modules refers to an important aspect of simulation. Figure 1 shows the framework of the capability-enhanced PARAMICS simulation environment. Any an API module in the enhanced PARAMICS environment exchanges dynamic data with the core PARAMICS model and other advanced API modules through the Dynamic Linking Library (DLL) mechanism.

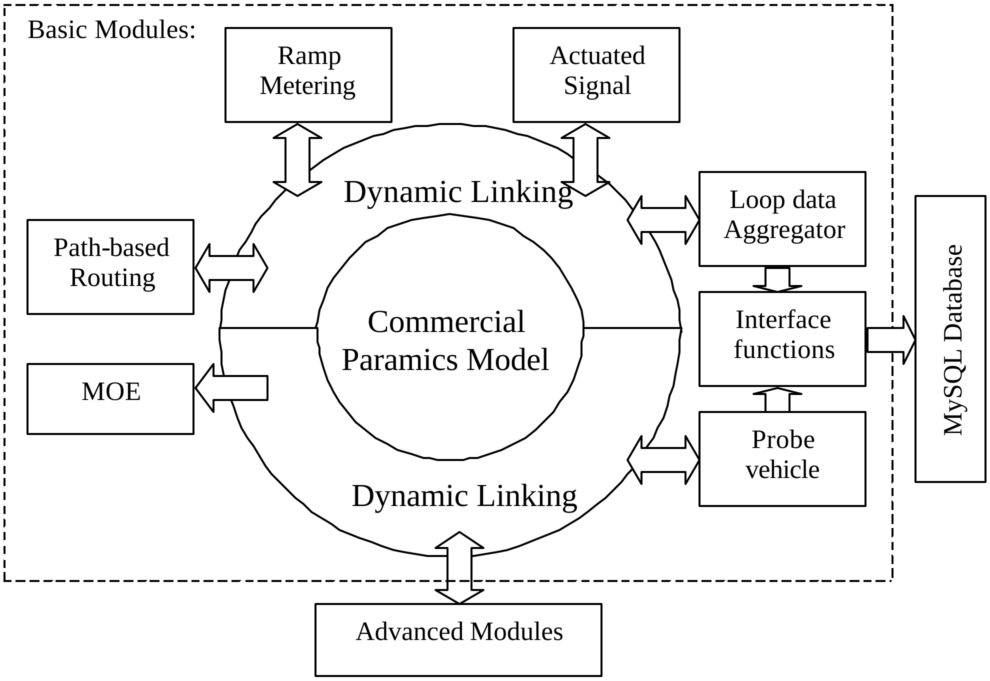

Figure 1 Framework of the capability-enhanced PARAMICS simulation

2.3.2 How API works

PARAMICS provides users with an API library that include a set of interface functions, which can be used to access its core models. Basically, PARAMICS provides two groups of interface functions, callback functions and control functions. The callback functions are used for providing information about the attributes of vehicles and their environment. There are two types of control functions, override and overload functions. Override functions are used to replace an internal function of standard simulation loop, such as car-following models. Overload functions are used to add additional functions to the PARAMICS simulation loop.

As shown in Figure 2, the simulation process is like this: after the start of simulation, some basic elements of the simulation, such as the speed and position of vehicles, traffic signals, etc., are updated at every time step. If an API module is involved in the simulation, it may work at every time step, or be triggered at a specific simulation time or by a specific event. In general, an API module gets necessary information from the simulation world through callback function and then affects the simulation through control functions.

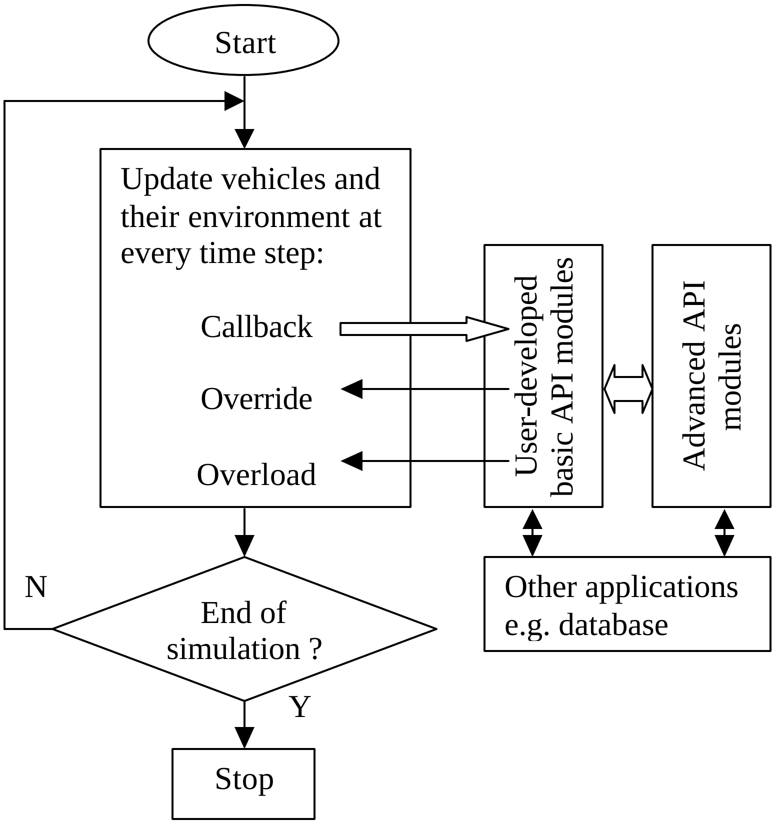

Figure 2 The PARAMICS simulation process with API modules

2.3.3 Implementation of basic control modules

The following three control modules, actuated signal control, ramp metering control and loop detector data aggregation, will be used as basic control modules to implement evaluated ITS strategies in this report. We will explain how they are implemented and what the logic they have in this section. Except them, MOE will be described later in section 5. Path-based routing and database connection are not used in this study and thus they will not be explained.

2.3.3.1 Full-actuated Signal Control

This plug-in module implements the eight-phase, dual-ring, concurrent controller logic. The data input to this API is the signal timing plan, the geometry and detector information of each intersection. Interface functions have been provided by this API for external modules to acquire and change the default timing plan. This API provided a couple of interface functions for external API modules to acquire the current signal timing plan and set a new timing plan to a specific signal. An advanced signal control algorithm API can be further developed based on them. The prototypes of these interface functions are shown below.

Signal* signal_get_parameters(char *nodeName);
Function: Querying the current signal timing plan of a specific actuated signal
Return Value: The current timing plan of an actuated signal.
Parameters: **nodeName** is the name of the signal node.
Signal is the structure of actuated signal data, whose definition is:

```
type Signal
{
        // intersection name and location
        char *node;
        char *controllerLocation;

        // signal parameters
        int movements[8];
        float maximumGreen[8];
        float minimumGreen[8];
        float extension[8];
        float storedRed[8];
        float phaseGreenTime[8];
        float movementGreenTime[8];

        // current phase information
        int currentPhase;
        int expiredTime;
        float redTimeLeft;
        Bool cycleEndFlag;    };
```

Void signal_set_parameters(Signal *sig);
Function: Setting a new timing plan to a specific signal.
Return Value: None
Parameters: **sig** stores the new timing plan.

2.3.3.2 Ramp Metering Control

This plug-in module is designed to model pre-timed ramp metering control on either one-car-per-green basis or n-cars-per-green basis (with n > 1). It also supports multiple timing plans, HOV bypass, and the use of ramp detectors for metering control. The data input of this API is a time-of-day ramp control plan and the detector information of each meter. In addition, this API provided a couple of interface functions for external API modules to acquire the current metering rate and set a new metering rate to a specific ramp meter. An advanced ramp-metering algorithm API can be further developed based on these interface functions. The prototypes of them are shown below.

RAMP *ramp_get_parameters (char *rampnode)

Function: Querying the current metering plan of a specific ramp meter.

Return Value: The current metering control plan of an on-ramp signal.

Parameters: **rampnode** is the name of an on-ramp signal node.

RAMP is the structure of ramp control data, whose definition is:

```
type Ramp
{
// on-ramp signal node name and its location
char    *rampNode;
char    *controllerLocation;
// ramp control types and parameters
int     ControlType;
float   meteringCycle;        };
```

Where **controlType** is the status (or type) of the ramp metering control, which can be 0 (if RAMP_CLOSURE), 1 (if RAMP_ON with single-entry metering), 2 (if RAMP_ON with platoon metering) and 9 (if RAMP_OFF).

void ramp_set_parameters (RAMP *ramp, Bool staus)

Function: Setting a new metering rate to a specific ramp meter.

Return Value: None

Parameters: **ramp** stores the new metering control data of a specific on-ramp; **status** is a Boolean value. **status** = TRUE means to set a new metering rate based on an external algorithm; **status** = FALSE means to restore the default time-of-day timing plans.

2.3.3.3 Loop detector data aggregation

In the real world, loop detectors are placed on freeways and arterials for collecting aggregated data at a certain time interval (typically, 30 seconds) for the purposes of traffic analysis and traffic control. These aggregated loop data are stored either in the database or shared memory. Other traffic operation components can get access to these data through data communication networks and use them for generating real-time control strategies.

The loop data aggregator API works as the traffic data collection and provision server in the enhanced PARAMICS environment. It emulates the real-world data collection from inductive loop detectors and broadcasts the latest aggregated loop data to the dynamic memory during simulation. Other API modules can obtain these data in real time through the interface function provided by this API. In addition, this API can report the aggregated loop data to text files or the MYSQL database as performance measures for data analysis and performance comparison.

The interface function of this API can be used for querying the aggregated loop data at a detector station at a certain time interval. The aggregated loop data includes grouped volume, average occupancy and average speed, as well as lane-based volume, average occupancy and average speed.

LOOPAGG loop_agg (char *detectorName)
Return Value: The aggregated detector data of a loop detector
Parameters: **detectorName**: loop detector name
LOOPAGG is a structure that has the following definition:

```
type LOOPAGG
{
int     detectorIndex;
float   AggregationTime;
int     lane;
int     g_vol;
float   g_occ;
float   g_spd;
int     *vol;
float   *occ;
float   *spd;   };
```

where
detectorIndex is the network-wide index for the detector;
Aggregation*time* is the time of the latest aggregation, determined by the loop data collection interval;
g_vol is the total traffic counts passing all lanes of a detector station;
g_occ is the average occupancy of all lanes at a detector station;
g_spd is the average speed of all vehicles passing a detector station;
lane is the total number of lanes at the detector station;
**vol, *occ, *spd* are pointers for recording values of volume, occupancy and average speed at each lane of a detector station.

2.4 Hierarchical API development

A complicated ITS strategy, such as integrated control, includes several ITS components. They can be regarded as an advanced module. The advanced module also refers to those advanced algorithms such as adaptive ramp-metering algorithms. These advanced modules are generally developed on top of basic enhancement modules, such as actuated signal control, ramp metering, and loop data aggregation. This hierarchical API development approach, demonstrated in Figure 3, can thus re-use the codes developed in the basic modules.

This hierarchical development of API enables customization and enhancements of various aspects of simulation modeling. The plug-in modules provide the user more freedom to control the simulation processes and hence overcome some challenges faced in modeling some ITS features. As a result, various ITS applications, can be easily tested and evaluated in this capability-enhanced micro-simulation environment.

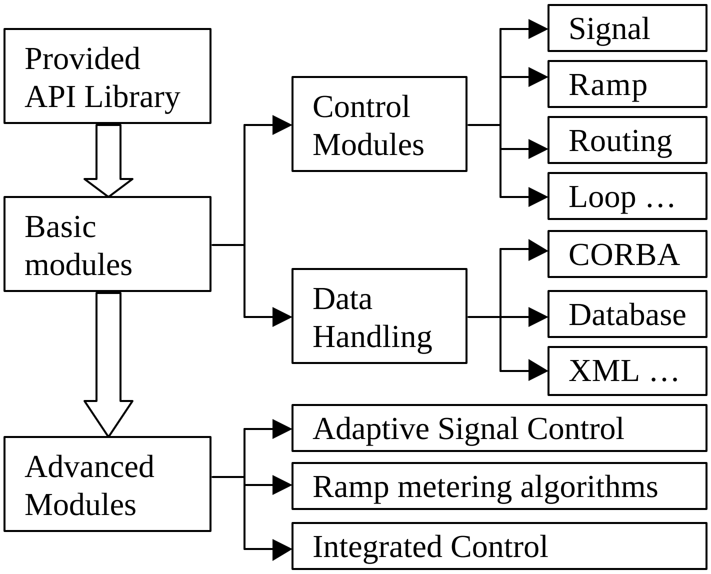

Figure 3 The hierarchical API development approach

2.5 Evaluation procedure

The established capability-enhanced PARAMCIS environment can thus be used to model the current traffic conditions and various potential ITS strategies as well. We take the following steps to evaluate an ITS application in the PARAMICS microscopic simulation environment:

2.5.1 Network coding and calibration

The study network needs to be modeled in the micro-simulator based on network layout overlays or aerial photos of the target area and the related geometry and infrastructure information. Significant efforts may be required to calibrate the network. Without calibration, the model network cannot be used for any application.

2.5.2 Modeling the evaluated ITS strategy

The evaluated ITS strategy, such as an adaptive ramp metering control, need to be modeled through API programming based on those basic modules already developed in the micro-simulator.

2.5.3 Implementation of the ITS strategy

Each ITS strategy may have some parameters, which should be set up based on the exclusive features of the study network or user’s assumptions. Some ITS applications, such as adaptive ramp metering algorithms, need a detailed calibration process.

2.5.4 Performance evaluation

Based on the features of the evaluated ITS strategy and objectives of the evaluation study, a number of performance measures should be selected for benefit and performance analysis. These measures either can be extracted directly from the output of simulation runs or obtained from developed APIs.

2.5.5 Result discussions

If there exist unexpected results, the previous steps need to be checked to ensure the correctness of the results. Results then can be used for decision-making.

3 NETWORK MODEL CALIBRATION

3.1 Study site and calibration data acquisition

3.1.1 Study site

The study network is a highly congested corridor network in the city of Irvine, Orange County, California, illustrated in Figure 4. The network includes a 6-mile section of freeway I-405, a 3-mile section of freeway I-5, a 3-mile section of freeway SR-133 and the adjacent surface streets.

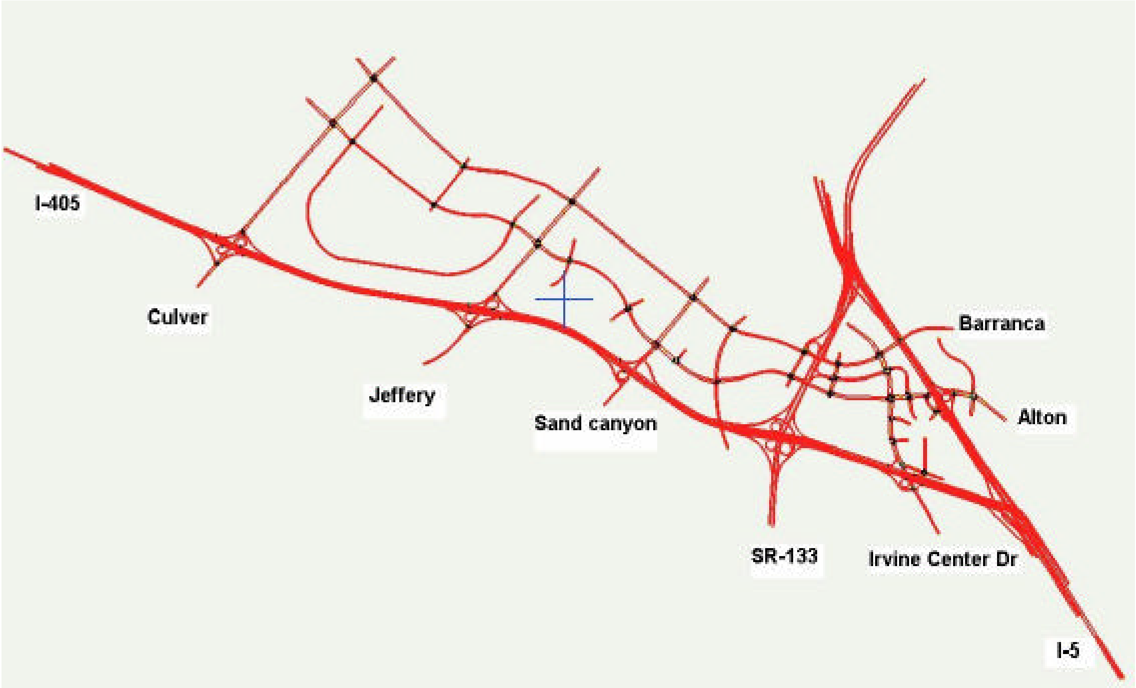

Figure 4 Overview of the study network

3.1.2 Network coding

We built the study network in PARAMICS based on the aerial photo of the target area and related road geometry and infrastructure information obtained from Caltrans and the city of Irvine. The simulated network has the same geometry, the same traffic control operations, including actuated signal control and time-based ramp metering, and the same configuration of ITS facilities, including loop detectors and VMS, as those in the real world. There are 38 actuated signals and 16 fixed-time metered on-ramps, which are modeled by the full-actuated signal API and ramp metering API respectively. The signal timing and ramp metering plans currently in place are used as the baseline of this study.

The zone structure of the network is based on information obtained from the OCTAM (Orange County Transportation Authority travel demand Model) model. A static AM peak OD matrix, sub-extracted from the OCTAM 2000 model, is used as the reference OD matrix of this study.

The calibration efforts for a simulation study ultimately require comparing simulated data with field-observed traffic data. Because field observations vary from day to day due to the stochastic nature of traffic, our calibration objective is to re-construct the typical real-world traffic variation in the PARAMICS simulation. The calibration efforts are focused on the use of aggregated data to calibrate the most critical parameters in PARAMICS, including OD matrix adjustment, route choice parameters, the mean target headway and driver reaction time, and signposting settings of important freeway links in PARAMICS.

3.1.3 Preparation of calibration data

The following data are obtained in order to calibrate the study network in PARAMICS.

3.1.3.1 Arterial volume data

(1) 15-minute interval traffic counts at arterial links acquired from the City of Irvine (most of them collected at January of 2002, and June of 2001). Some of links are located at cordon points of the network and others are located at important links inside the network.
(2) Traffic counts at important cordon points of the network (not covered by the data from the City of Irvine), obtained from data processing of the surveillance video data (taped between March 27, 2002 to April 19, 2002).

3.1.3.2. Freeway loop detector data

All available loop data of freeway loop detectors (including mainline, on-ramp and off-ramp loops in the study area) at 30-second interval, acquired from the database for the time period from Oct 1, 2001 to Oct 30, 2001. These 30-second data are further aggregated to 5 minutes interval for the traffic volume match.

3.1.3.3. Travel time data

Freeway floating car data (Nov. 17, 2001) of northbound and southbound freeway I-405, obtained from Caltrans District 12.

3.1.3.4. Reference OD matrix

The O-D matrix derived from the OCTAM model is only for the morning peak hour from 6 to 9 AM. Since the congestion happened in the study network cannot be totally cleared at 9 AM, the OD demand matrix is further expanded to 4 hours, i.e. from 6 to 10 AM, based on the observed 15-minute traffic counts and freeway loop data at cordon points.

3.1.3.5. Vehicle performance and characteristics data

These data include vehicle length, maximum speed, maximum acceleration and deceleration rate, etc., which are obtained from Caltrans.

3.1.3.6. Vehicle mix by type

Vehicle mix by type is determined by the statistical analysis of vehicle types, based on the surveillance videos at two locations in the network.

3.1.4 Preliminary data analysis

Since the study network is a corridor network where freeways play an important role, we need to make a preliminary data analysis on freeway loop data in order to find a set of typical loop data that can reflect the real-world traffic variations for this calibration study.

We select several loop data stations located at the upstream end of each freeway, all on-ramps and all off-ramps for this analysis. 11 weekdays within a month of loop data at these stations are obtained from our database. Then the total volume of peak hour, i.e. 7-8 AM, and the whole period, i.e. 6-10AM, of each loop station are calculated and compared. Since more than 85% of total volumes at loop stations on October 17, 2001 are close to the mean of the 11 days, the loop data of October 17, 2001 can represent the typical traffic condition of the study network and are used to calibrate our model network.

3.2 Calibration

PARAMICS Build 3.0.7 is used in this study. PARAMICS regards each vehicle in the simulation as a Driver Vehicle Unit (DVU). Simulation relies on characteristics of drivers and vehicles, the interactions between vehicles, and the network geometry. Prior to this study, the PARAMICS model has been applied in California extensively and a lot of calibration and validation efforts have been conducted (Abdulhai, et al, 1999, Lee, et al, 2001, Gardes, et al, 2002, Chu, et al, 2002). Most previous applications focused on freeway network and did not consider how to calibrate a corridor network consisting of both freeway and its adjacent parallel streets.

Except network geometry data and signal control data, the basic input data to the network model also include vehicle mix by type of the study network, vehicle characteristics and performance data, and some driving restrictions. In addition, the following options are required to be assumed first:

(1) Drivers' behaviors are determined by two factors, aggressiveness and awareness, which should be assumed before the calibration. We assume them as normal distribution.

(2) Due to the existence of freeways and its parallel streets in the study network, the routing algorithm adopted in the simulation is important. Stochastic assignment (with 5% perturbation) is used for this calibration process. Stochastic assignment in PARAMICS assumes that different drivers perceive different costs from a decision node to the destination. The perceived cost is calculated based on the given perturbation factor with a random number assigned to the vehicle, and the shortest perceived route is chosen at the decision node.

The flow chart of the calibration process is shown in Figure 5.

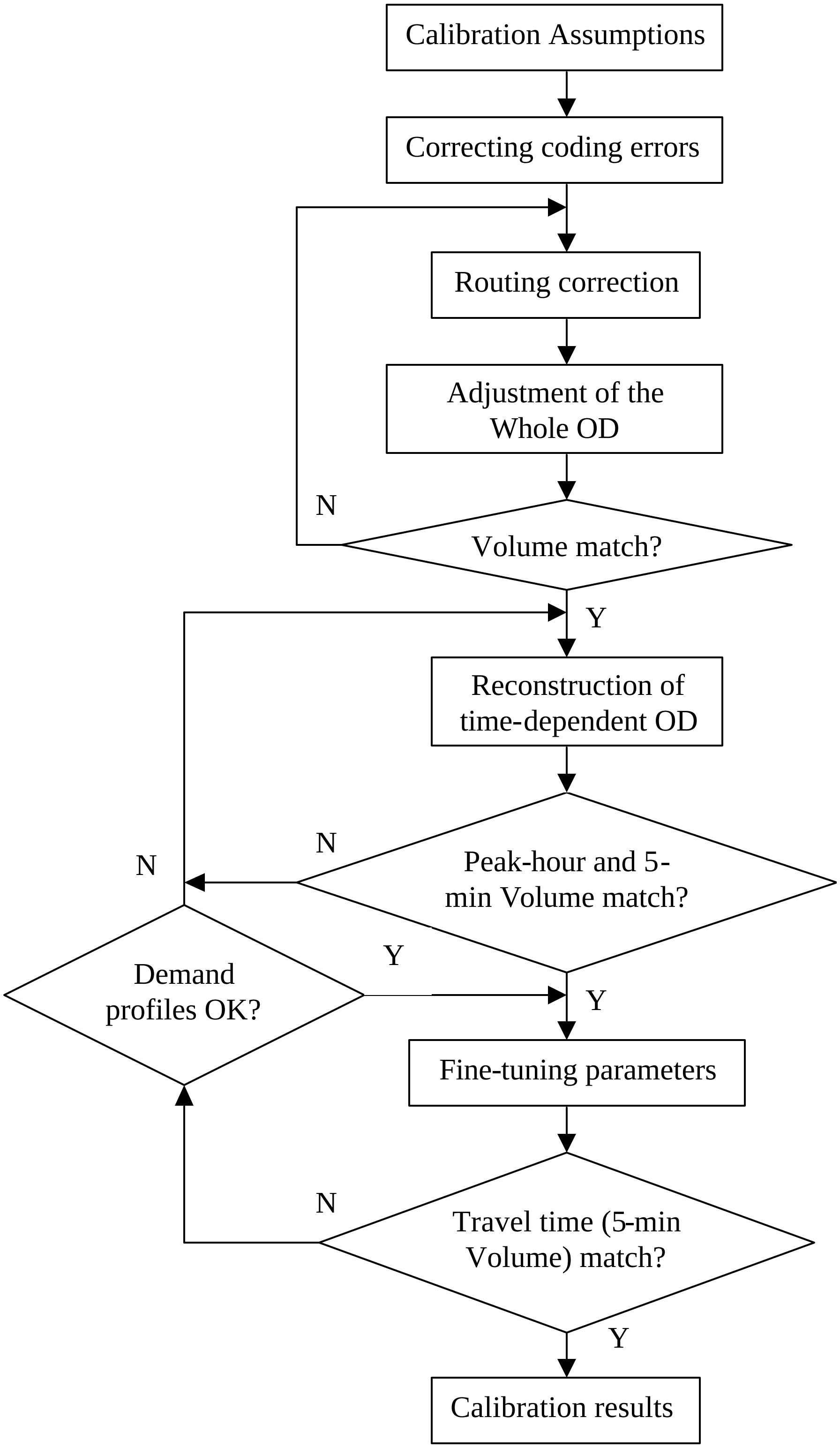

Figure 5 Flow chart of calibration procedure

3.2.1. Checking coding errors

At this step, the reference OD matrix is evenly loaded for the whole simulation period (subject to a flat demand "profile"), without considering the variation of demands over time. All critical parameters of PARAMICS use default values. The vehicles are observed as vehicles move through the network. Abnormal behaviors always correspond to network coding errors, which need to be identified and solved.

3.2.2. Adjustment of the OD matrix and modification of route choices

The objective of this step is to estimate a whole OD matrix of the network based on a fixed traffic assignment method and its resulting route choice. It is a static OD demand estimation problem, which is underdetermined and uses less traffic flow information on the network links to estimate the intensity of traffic flow between each origin and destination of travel. There are many static OD estimation methods. The least square estimation method is most frequently used. See Cascetta (1994) and Bell (1991) for example.

The reference OD matrix obtained from the OCTAM model is not accurate because the data sets of OCTAM model are generally limited to the nearest decennial census year and the sub-extracted OD matrix is generated based on the four-step model of TRANPLAN. Since we have 15-minute interval traffic counts at all cordon points of the network, the total traffic attractions and generations (or the total inbound and outbound traffic counts) of each zone are known. We assume the same trip distribution as that of the reference OD matrix is applied to all zones in the adjusted OD matrix. The FURNESS technique is then used for balancing the OD table. If the total attractions are not equal to the total generations, the total generations are used as the total. For the following steps of OD modification, the total origin and destination demands will be basic constraints.

Then we evenly load this adjusted OD matrix for the whole simulation period (subject to a flat demand "profile"). Based on the simulation results, we can compare the observed and simulated total traffic counts at selected measurement locations with the objective function shown below:

$$\min \quad \sum_{n=0}^{N} (M_{obs}(n) - M_{sim}(n))^2 \tag{1}$$

where N is the total number of measurement locations, which are generally loop detector stations in the real world; $M_{obs}(n)$ and $M_{sim}(n)$ are total observed and simulated traffic counts at measurement location n for the whole study period, respectively. Selected measurement locations include the freeway loop stations at on-ramps, off-ramps and along the mainline freeway, and several important arterial links.

An iteration process is required in order to obtain a satisfactory whole OD matrix. If the above indices cannot be satisfied, we need to make some modifications to vehicle routing and the reference OD matrix as well. Vehicle routing is determined by the traffic assignment method used, i.e. stochastic assignment, in this study. Since the travel delays caused by the intersection signal and freeway ramp control are not considered for traffic assignment in PARAMICS, the route choice may need to be adjusted through adding tolls to related decision links.

The method used for modifying OD is proportion control (Robillard, 1975). We assume the link-flow proportions (at all measurement locations) are constant for a simulation run, which can be calculated based on simulation results. We develop an API that can report the statistical information about vehicles passing all measurement points. There is an order issue during the modification of OD. The freeway loop stations at on-ramps, off-ramps, and mainline loop stations at cordon points of the network are analyzed first for the possible OD modification because the flows passing these points have fewer origin and destination combinations. The other mainline loop stations are considered next.

The measure of the overall quality of the calibration is the GEH statistic, used by British engineers (UK Highways Agency, 1996):

$$GEH = \sqrt{\frac{\left(M_{obs}(n) - M_{sim}(n)\right)^2}{(M_{obs}(n) + M_{sim}(n))/2}} \qquad (2)$$

If the GEH values for more than 85% of the measurement locations are less than 5, the adjusted OD is acceptable.

Based on multiple iterations, the calibration results at this step, i.e. the comparison of observed and simulated traffic counts at selected measurement locations are shown in Table 1, which have satisfied the calibration acceptance criteria of this step.

3.2.3 Reconstruction of time-dependent OD demand

The objective of this step is to assign the whole OD to a series of consecutive time slices. Our method tries to simplify the complex time-dependent OD estimation problem through reconstructing the dynamic OD demands based on a set of demand profile assumptions. The examples of time-dependent OD estimation methods can be found in the following references, Hu et al. (2002), Cascetta et al. (1993), Tavana et al. (2001).

PARAMICS has an enhanced feature of demand loading, i.e. the ability to specify different profiles for each OD pair. Through the use of “matrix” and “profile” files, a different profile can be specified for a different OD pair. Since the 15-minute interval traffic counts at all cordon points of the network are known, the profile of vehicle generation from any origin zone and that of the vehicle attraction to any destination zones are thus known.

The next question is how to find the demand profile for each OD pair. We further assume a number of initial demand profiles for all OD pairs based on the following criteria:

- The demand profile from an arterial origin zone to any an arterial destination zone has the same profile, which is the same as the vehicle generation profile from this origin zone
- The demand profiles from a freeway origin zone to a freeway destination zone, from a freeway origin zone to an arterial destination zone, from an arterial origin zone to a freeway destination zone will be based on the traffic count profile at correspondent loop detector stations located at freeway mainline, off-ramp, and on-ramp, respectively.

Since the mean target headway and driver reaction time are two key user-specified parameters in the car-following and lane-changing models that can drastically influence overall driver behaviors of the simulation, we select a couple of smaller values for them (i.e., 0.8 and o.6, respectively) in order to test the correctness of our assumptions of demand profiles without the involvement of strong queuing phenomena in the network.

This step has two calibration objective functions. The first one is an easy one, which is to minimize the deviation between the observed and corresponding simulated traffic counts at selected measurement locations for the peak hour of the simulation period:

$$\min \quad \sum_{n=0}^{N} (M_{obs}(n, peak\_T) - M_{sim}(n, peak\_T))^2 \qquad (3)$$

where N is the total number of measurement locations; $M_{obs}(i, peak\_T)$ and $M_{sim}(i, peak\_T)$ are total observed and simulated traffic counts for the peak hour at measurement location i, respectively. The selected measurement points are the same as those in last step. The peak hour is defined as from 7 to 8 AM. The following criteria are required to be satisfied for this objective:

- The modeled peak hour volumes at measurement locations must be within 15 percent of the observed volumes for flows greater than 700 vphpl, or within 100 vph for flows less than 700 vph. These targets must be satisfied for 85 percent of the cases;
- Total screenline flows (normally >5 links) to be within five percent for nearly all screenlines;
- The GEH statistic to be less than five for individual flows for 85 percent of the cases, and less than four for screenline totals for nearly all screenlines;

The second objective function is to minimize the deviation between the observed and corresponding simulated traffic counts at selected measurement locations at five-minute interval. It can be formulate as:

$$\min \quad \sum_{t=1}^{T} \sum_{n=1}^{N} (M_{obs}(n,t) - M_{sim}(n,t))^2 \qquad (4)$$

where N and T are the number of measurement locations and time periods, respectively; $M_{obs}(n, t)$ and $M_{sim}(n, t)$ are observed and simulated traffic counts of time period t at measurement location i, respectively. The length of each period is 5 minutes in this study.

The measure of goodness of fit we used is the mean abstract percentage error (MAPE), which can be calculated by:

$$MAPE = \frac{1}{T}\sum_{t=1}^{T}((M_{obs}(t) - M_{sim}(t)) / M_{obs}(t)) \tag{5}$$

We expect to obtain smallest MAPE errors at all measurements.

This step of calibration is an iterative process. We mainly modify the demand profiles from a freeway origin zone to a freeway destination zone, from a freeway origin zone to an arterial destination zone, and from an arterial origin zone to a freeway destination zone in order to match the traffic counts at selected measurement locations. The trial-and-error method is used for the modification of demand profiles based on the following criteria.

- The profile from a freeway origin zone to an arterial destination zone can be estimated based on the 15-minute loop data at a corresponding off-ramp location.
- The profile from an arterial origin zone to a freeway destination zone can be estimated based on the 15-minute loop data at a corresponding on-ramp location.
- The profiles from freeway origin zones to freeway destination zones are decided last.

The traffic count calibration at this step is just an initial match of volume data and the next step will fine-tune this volume calibration. The calibration results of this step are shown in Table 1, which shows the comparison of traffic counts of peak hour at those selected measurement locations. Figure 6 shows the calibrated demand profiles for several major OD pairs.

3.2.4. Parameter fine-tuning

This step will fine-tune various parameters in order to re-construct the traffic variations during the study period. These parameters include:

- Link specific parameters, including the signposting setting or the target headway of those links at critical bottleneck locations where a very minor change in capacity can have a major effect on congestion.
- Parameters for the car-following and lane-changing models, i.e., the mean target headway and driver reaction time. They are two key user-specified parameters in the car-following and lane-changing models that can drastically influence overall driver behaviors of the simulation.
- Demand profiles from freeway origin zones to freeway destination zones may need to be further modified in order to adapt traffic congestion along freeways.

Table 1 Traffic counts calibration results of the whole AM peak period and the peak hour

	Peak Hour (7-8 AM)				AM Peak Period (6-10 AM)			
Mainline Detectors	**Observed**	**Simulated**	**% diff**	**GEH**	**Observed**	**Simulated**	**% diff**	**GEH**
405n0.93ml	6803	6808	**0%**	**0.06**	24505	24428	**0%**	**0.49**
405n3.31ml	9127	9006	**-1%**	**1.27**	33274	32646	**-2%**	**3.46**
495n3.86ml	8322	8248	**-1%**	**0.81**	30589	29890	**-2%**	**4.02**
405n5.74ml	9545	9377	**-2%**	**1.73**	34277	33475	**-2%**	**4.36**
405s6.21ml	7960	8135	**2%**	**1.95**	28255	27904	**-1%**	**2.09**
405s3.31ml	8098	8010	**-1%**	**0.98**	28501	27795	**-2%**	**4.21**
405s0.77ml	5583	5514	**-1%**	**0.93**	20057	19638	**-2%**	**2.97**
5n22.2ml	7533	7686	**2%**	**1.75**	26830	26614	**-1%**	**1.32**
5s22.14ml	6499	6974	**7%**	**5.79**	24464	24025	**-2%**	**2.82**
133n9.37ml	510	471	**-8%**	**1.76**	1496	1498	**0%**	**0.05**
133n10.05ml	804	817	**2%**	**0.46**	2534	2607	**3%**	**1.44**
133s10.05ml	2752	2674	**-3%**	**1.50**	8557	8557	**0%**	**0.00**
133s9.37ml	1760	1652	**-6%**	**2.61**	5233	5429	**4%**	**2.68**
Ramp Detectors								
405n0.93fr	160	162	**1%**	**0.16**	546	564	**3%**	**0.76**
405n0.93orb	512	507	**-1%**	**0.22**	1815	1760	**-3%**	**1.30**
405n1.11orb	110	149	**35%**	**3.43**	447	445	**0%**	**0.09**
405n1.73ff	56	54	**-4%**	**0.27**	213	197	**-8%**	**1.12**
405n1.93ff	2227	2166	**-3%**	**1.30**	6887	6987	**1%**	**1.20**
405n2.99fr	165	196	**19%**	**2.31**	726	705	**-3%**	**0.79**
405n2.99orb	436	442	**1%**	**0.29**	1418	1358	**-4%**	**1.61**
405n3.86fr	709	731	**3%**	**0.82**	2737	2704	**-1%**	**0.63**
405n3.86orb	307	320	**4%**	**0.73**	931	963	**3%**	**1.04**
405n4.03orb	816	809	**-1%**	**0.25**	2889	2686	**-7%**	**3.84**
405n5.55fr	460	426	**-7%**	**1.62**	1626	1659	**2%**	**0.81**
405n5.55orb	682	670	**-2%**	**0.46**	2161	2134	**-1%**	**0.58**
405n5.74orb	1026	1075	**5%**	**1.51**	3567	3576	**0%**	**0.15**
405s5.69fr	853	959	**12%**	**3.52**	3182	3139	**-1%**	**0.76**
405s5.69orb	316	276	**-13%**	**2.32**	983	921	**-6%**	**2.01**
405s5.5orb	241	281	**17%**	**2.48**	940	914	**-3%**	**0.85**
405s4.03fr	409	392	**-4%**	**0.85**	1602	1554	**-3%**	**1.21**
405s4.03orb	183	212	**16%**	**2.06**	647	664	**3%**	**0.66**
405s3.84orb	624	567	**-9%**	**2.34**	2112	1904	**-10%**	**4.64**
405s2.88fr	864	817	**-5%**	**1.62**	2937	2743	**-7%**	**3.64**
405s2.88orb	152	159	**5%**	**0.56**	468	505	**8%**	**1.68**
405s1.58ff	592	573	**-3%**	**0.79**	1881	1953	**4%**	**1.64**
405s1.57ff	70	117	**67%**	**4.86**	315	319	**1%**	**0.22**
405s0.96fr	1546	1496	**-3%**	**1.28**	4906	4907	**0%**	**0.01**
405s0.96orb	20	33	**65%**	**2.53**	58	123	**112%**	**6.83**
405s0.77orb	9	11	**22%**	**0.63**	43	43	**0%**	**0.00**
5n22.1fr	742	802	**8%**	**2.16**	2443	2600	**6%**	**3.13**
5n22.1orb	84	94	**12%**	**1.06**	289	339	**17%**	**2.82**
5n22.2orb	199	232	**17%**	**2.25**	752	735	**-2%**	**0.62**
Arterial Detectors								
Jeffery 405-Alton	2119	1963	**-7%**	**3.45**	6563	6317	**-4%**	**3.07**
	882	1057	**20%**	**5.62**	3520	3505	**0%**	**0.25**
Alton E of Jeffery	758	604	**-20%**	**5.90**	1987	2038	**3%**	**1.14**
	439	446	**2%**	**0.33**	1470	1386	**-6%**	**2.22**
Alton E of Sand	624	443	**-29%**	**7.84**	1675	1480	**-12%**	**4.91**
	729	777	**7%**	**1.75**	2443	2469	**1%**	**0.52**
Alton E of Laguna	804	619	**-23%**	**6.94**	2102	2382	**13%**	**5.91**
	491	606	**23%**	**4.91**	1714	1921	**12%**	**4.86**
Barranca SR133-ICD	428	420	**-2%**	**0.39**	1287	1240	**-4%**	**1.32**
	959	962	**0%**	**0.10**	3235	3161	**-2%**	**1.31**

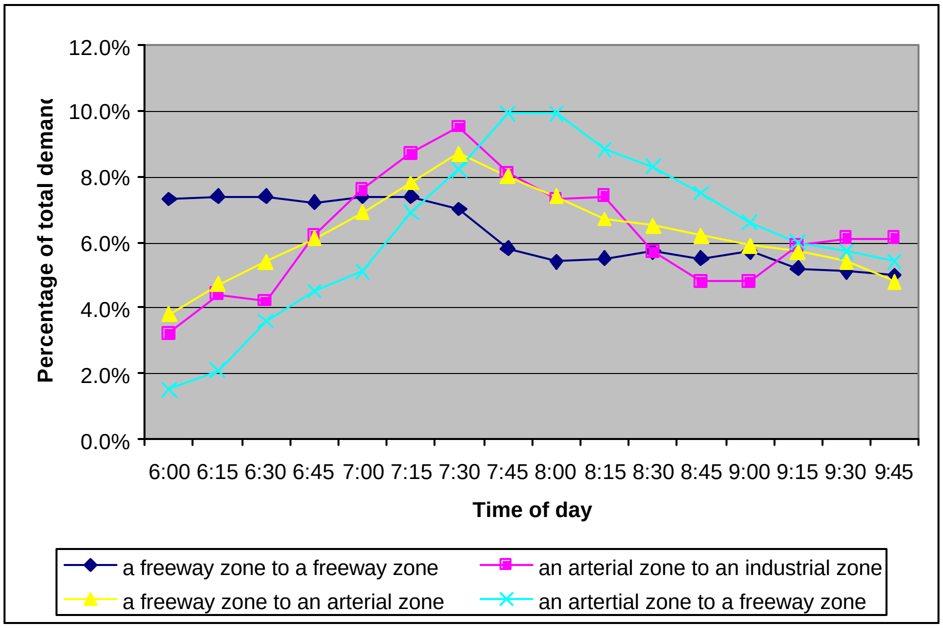

Figure 6 Demand profiles for major OD pairs

Section travel time is the major factor in this step because the main purpose of this step is to match the congestion pattern of the study network. In our study, the floating car data we have only covers two trips, i.e., between the interchanges at Irvine Center Drive and Culver Drive of both northbound and southbound freeway I-405. Since our network features a recurrent congestion along the northbound I-405, we select several loop detector stations on the northbound I-405 as the measurement points for volume match with the loop data of the same day of tach runs.

The objective function of this step is to minimize the deviation between the observed and corresponding simulated section travel time measurements between two selected measurement locations, and also traffic counts at measurement points. It can be formulated as Equation 4, but *M* can be traffic volume or section travel time. Section travel time and traffic counts are compared at 5-minute intervals.

Due to the high traffic demands during the peak hour, some network coding problems may show up and need to be corrected. Moreover, congestion and queuing phenomena on the northbound I-405 may take extra effort to modify demand profiles of some specific OD pairs. This step needs a lot of iterative simulation runs in order to find out the good combination of these aforementioned parameters. The trial-and-error method is used for parameter modification in this step. For an individual measurement location, the smallest MAPE error is expected. The calibration results of this step are shown in Table 2.

3.3 Calibration results

The final calibration cannot only be based on one single run because of the randomness of micro-simulations. For our case, we conducted 31 runs and pick the simulation results of the median one (based on the average system travel time) for the final comparison of calibration results.

We compare the simulation results with the loop data and the floating car data of Oct. 17, 2001. Figure 7 show that MAPE error of traffic counts at selected measurement locations range from 5.8% to 8.7%. Figure 8 and 9 show the comparison of observed and simulated section travel time for the northbound and the southbound I-405, which have the MAPE errors of 8.5% and 3.1%, respectively.

In general, simulated traffic counts and section travel time data correspond well to the measurements and accurately capture the congestion patterns of the target network shown on Oct. 17, 2001.

Table 2 Travel time calibrations

Travel time							
Mainline Trip Analysis	**Start time**	**Arrival Time**	**Observed**	**Start time**	**Arrival time**	**simulated**	**% diff**
Southbound I405 from Culver to ICD	6:00:22	6:04:38	256	6:00:00	6:15:00	264.5	7.0%
	6:25:14	6:29:36	262	6:25:00	6:30:00	257.8	3.3%
	6:47:01	6:51:17	256	6:45:00	6:50:00	255.7	5.4%
	7:06:34	7:10:56	262	7:05:00	7:10:00	259.6	1.7%
	7:24:45	7:28:54	249	7:25:00	7:30:00	263.1	5.9%
	7:46:23	7:50:48	265	7:45:00	7:50:00	278.9	1.1%
	8:05:14	8:09:41	267	8:05:00	8:10:00	326.8	0.3%
	8:24:23	8:28:44	261	8:25:00	8:30:00	262.6	0.6%
	8:43:42	8:47:47	245	8:45:00	8:50:00	259.5	2.1%
	9:04:27	9:08:34	247	9:05:00	9:10:00	246.4	3.2%
AMPE							3.1%
Northbound I405 from ICD to Culver	6:00:58	6:04:45	227	6:00:00	6:05:00	247.7	9.1%
	6:19:32	6:23:40	248	6:20:00	6:25:00	248.3	0.1%
	6:40:51	6:44:50	239	6:40:00	6:45:00	252.2	5.5%
	7:00:58	7:05:05	247	7:00:00	7:05:00	294.2	19.1%
	7:23:06	7:27:57	291	7:25:00	7:30:00	325.1	11.7%
	7:40:53	7:49:29	514	7:45:00	7:50:00	504.4	1.9%
	7:57:57	8:05:58	481	8:00:00	8:05:00	505.1	5.0%
	8:22:06	8:27:59	353	8:25:00	8:30:00	390.4	10.6%
	8:40:27	8:44:25	238	8:40:00	8:45:00	281.6	18.3%
	8:59:57	9:04:03	246	9:00:00	9:05:00	256.0	4.1%
AMPE							8.5%

Notes: AMPE – Abstract mean percentage error

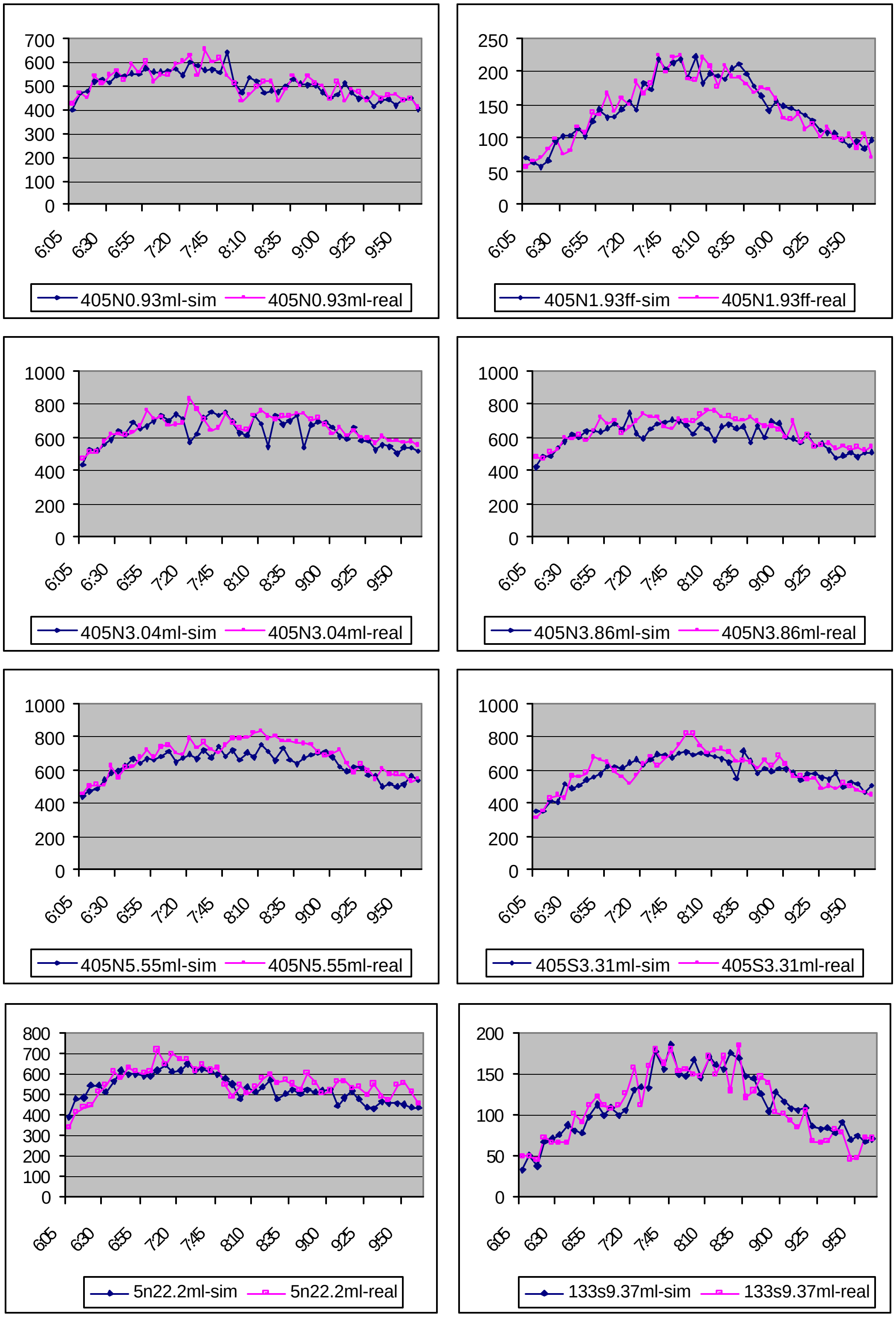

Figure 7 Traffic counts calibration (5-minute volume) at major freeway measurement locations

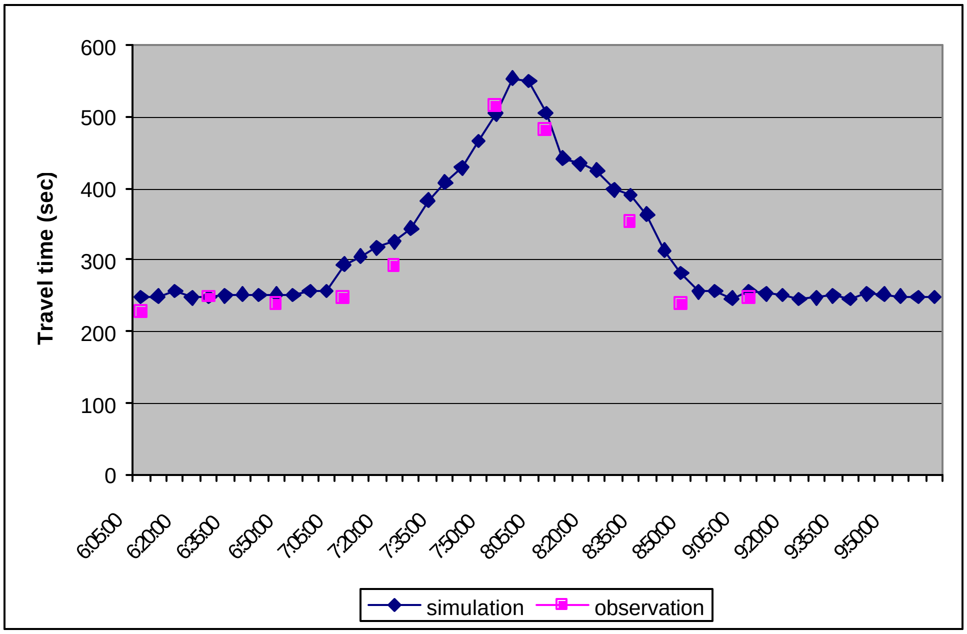

Figure 8 Comparison of observed and simulated travel time of northbound I-405

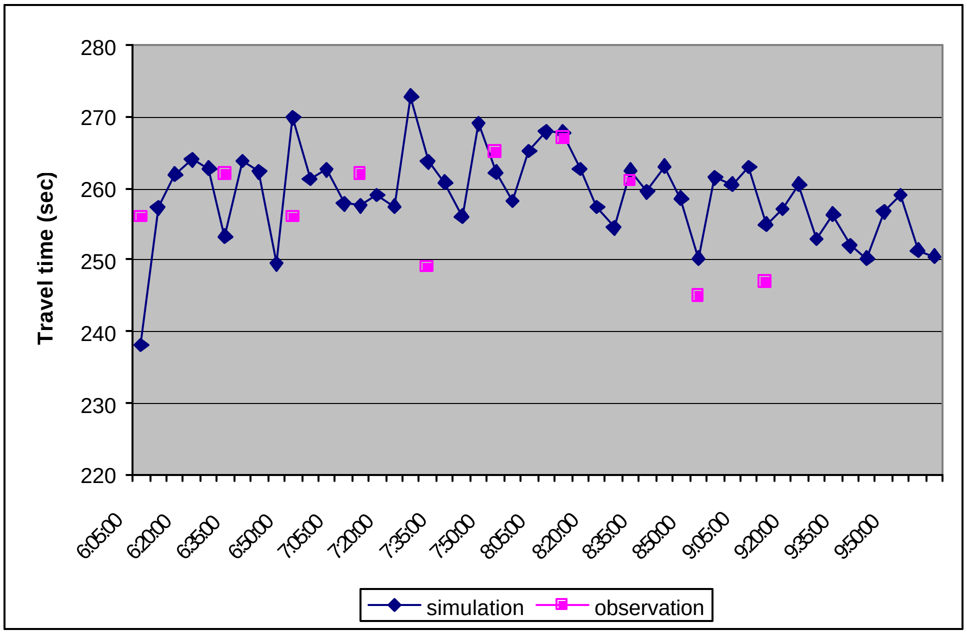

Figure 9 Comparison of observed and simulated travel time (unit: second) of southbound I-405

4 MODELING AND IMPLEMENTING ITS STRATEGIES

4.1 Potential ITS strategies

4.1.1 Problem description

Based on the analysis of the real-world loop data and floating car data, we found the northbound of freeway I-405 is highly congested from 7:30 to 8:30 AM due to the large amount of traffic merging to freeway I-405 from freeway SR-133 and Jeffery Dr. The bottleneck generated at Jeffery often spreads to the upstream as a backward shockwave, which further deteriorates the traffic condition at the upstream bottleneck at SR-133 since there is no additional lane on I-405 after SR-133 merges to I-405.

The historical incident data also shows that the merge area of SR-133 and I-405 (on the northbound I-405) is the location where incidents happen most frequently. Freeway incidents may take the form of complete blockage of one or more than one lane or slowdowns caused by incidents taken place on the shoulder. Here we simulate the latter to the simulation network. A shoulder incident is injected to the merge area of SR-133 and I-405 (on the northbound I-405) at 7:45 AM that is the time that incidents happen most frequently based on historical incident data. This incident causes the speed of passing vehicles to be 10 mph for the first ten minutes and 15 mph thereafter.

4.1.2 Solution Strategies

Based on the data from Caltrans, without any incident management, the average incident clearance time is 33 minutes; the existing incident management can decrease the clearance time to 26 minutes. An improved incident management is expected to further decrease the clearance time to 22 minutes. We then compare the following three scenarios for the incident management:

- Scenario 1: Non-incident management
- Scenario 2: Existing incident management
- Scenario 3: Improved incident management

Then we study on how other potential ITS strategies can help to relieve this non-recurrent congestion based on the existing incident management (26 minute of the clearance time). The potential ITS strategies we will evaluate are as follows.

- Scenario 4: Local adaptive ramp metering, ALINEA
- Scenario 5: Coordinated ramp metering, BOTTLENECK
- Scenario 6: Traveler information system
- Scenario 7: Combination - 1 (Adaptive signal control, fixed-time ramp metering, and traveler information)
- Scenario 8: Combination – 2 (Adaptive signal control, ALINEA ramp metering control, and traveler information)

4.2 Implementation of evaluated ITS strategies in PARAMICS

Each evaluation scenario includes one or more than one ITS strategies. We have described in Section 2 about our hierarchical API development framework, which facilitates the development of advanced ITS strategies based on basic ITS modules having been established. All simulation scenarios and their corresponding ITS strategies are illustrated in Table 3.

Table 3 Simulation scenarios and their corresponding control strategies

Scenario	Scenario description	ITS components			
		Ramp Metering	Signal Control	Traveler Information	Incident Management
0	BASELINE 2000	Fixed time	Coordinated	N/A	N/A
1	Non-incident management	Fixed time	Coordinated	N/A	33 mins
2	Existing incident management	Fixed time	Coordinated	N/A	26 mins
3	Improved incident management	Fixed time	Coordinated	N/A	22 mins
4	Local adaptive ramp metering	ALINEA	Coordinated	N/A	26 mins
5	Coordinated ramp metering	BOTTLENECK	Coordinated	N/A	26 mins
6	Traveler information	Fixed time	Coordinated	5% compliance	26 mins
7	Combination - 1	Fixed time	Synchro-Adaptive	5% compliance	26 mins
8	Combination - 2	ALINEA	Synchro-Adaptive	5% compliance	26 mins

4.2.1 Incident management

Scenario 1 is actually the baseline of this study. Scenario 2 and 3 apply incident management to relieve the congestion caused by the incident on the freeway shoulder, i.e. decreasing the incident clearance time through the fast responses to the incident. We develop an incident API to simulate this type of shoulder incident. Through changing the clearance time of the incident, we can easily model these three incident management scenarios.

The control parameters of this API are the location of the incident, the time when the incident happened, and the duration of the incident. The parameters can be found in section 4.1.

4.2.2 Actuated signal coordination

Since the coordinated actuated signal control is operated at some signalized intersections, we developed an actuated signal coordination API module for controlling those coordinated signals. Actuated signal coordination API is developed based on the basic control module, i.e. full actuated signal control API. The details about this API's control logic and how we implement it can be found in our previous report (Liu et al, 2001).

4.2.3 Adaptive ramp metering

Scenario 4 and 5 apply local adaptive ramp metering and coordinated ramp metering, respectively.

4.2.3.1 ALINEA

The local adaptive ramp-metering algorithm we use is ALINEA (Papageorgiou, et al, 1990 and 1991). ALINEA is a local feedback ramp metering policy, which attempts to maximize the mainline throughput by maintaining a desired occupancy on the downstream mainline freeway. Two detector stations are required for the implementation of the ALINEA algorithm. The first loop detector is located on the mainline freeway, immediately downstream of the entrance ramp, where the congestion caused by the excessive traffic flow originated from the ramp entrance can be detected. The second loop station is on the downstream end of the entrance ramp, and used for counting the on-ramp volume.

For an on-ramp under ALINEA control, its metering rate during time interval (t, t+ ?t) is calculated as:

$$r(t) = \tilde{r}(t - \Delta t) + K_R \bullet (O^* - O(t)) \qquad (6)$$

where ? t is the update cycle of ramp metering implementation; $\tilde{r}(t - \Delta t)$ is the measured metering rate of the time interval of (t –?t, t); O(t) is the measured occupancy of time interval (t –?t, t) at the downstream detector station; K_R is a regulator parameter, used for adjusting the constant disturbances of the feedback control; O* is the desired occupancy at the downstream detector station. The value of O* is typically set equal to or slightly less than the critical occupancy, or occupancy at capacity, which can be found in the volume-occupancy relationship.

4.2.3.2 BOTTLENECK

The coordinated ramp-metering algorithm we use is BOTTLENECK, applied in Seattle, Washington (Jacobsen, et al, 1989). Basically, there are three components in the algorithm: a local algorithm computing local-level metering rates based on local conditions, a coordination algorithm computing system-level metering rates based on system capacity constraints, and adjustment to the metering rates based on local ramp conditions. The original BOTTLENECK algorithm uses the occupancy control as its local metering algorithm. In this study, we replace its native local control algorithm with ALINEA because ALINEA is easier to be calibrated and performs better than the occupancy control.

The coordination algorithm is the unique aspect of BOTTLENECK. The freeway segment under control is divided into several sections, each of which is defined by the stretch of freeway between two adjacent mainline loop stations. A section is identifies as a bottleneck if it satisfies two conditions, i.e. capacity condition and vehicle storage condition. The capacity condition can be described as:

$$O_{down}(i,t) \geq O_{threshold}(i) \tag{7}$$

where $O_{down}(i, t)$ is the average occupancy of the downstream detector station of section i over the past one-minute period $(t-1, t)$; $O_{threshold}(i)$ is a pre-defined loop station occupancy threshold when it is operating near capacity. The vehicle storage condition can be formulated as:

$$Q_{reduction}(i,t) = (Q_{up}(i,t) + Q_{on}(i,t)) - (Q_{off}(i,t) + Q_{down}(i,t)) \geq 0 \tag{8}$$

where $Q_{reduction}(i, t)$ is the number of vehicles stored in section i during the past minute. $Q_{up}(i, t)$ and $Q_{down}(i, t)$ are the volume entering section i across the upstream detector station and the volume exiting section i across the downstream detector station during the past minute, respectively; $Q_{on}(i, t)$ is the total volume entering section i from on-ramps during the past minute; $Q_{off}(i, t)$ is the total volume exiting section i to off-ramps during the past minute.

The number of vehicles stored in the bottleneck section $Q_{reduction}(i, t)$ should be reduced. Each section needs to define an area of influence that consists of a number of upstream on-ramps for the volume reduction. The amount of volume reduction from an on-ramp is determined by a weighting factor, pre-defined according to how far it is to the downstream detector station of the bottleneck section and the historical demand pattern from the on-ramp. If on-ramp j involves in the volume reduction of any bottleneck section, its system-level metering rate is calculated as:

$$r(j,t) = Q_{on}(j,t-1) - \underset{i=1}{\overset{n}{MAX}}(Q_{reduction}(i,t) \bullet ((WF_j)_i / \sum_j (WF_j)_i)) \tag{9}$$

where $\underset{i=1}{\overset{n}{MAX}}$ is defined as the operator of selecting the maximum volume reduction if the on-ramp is located within more than one section's area of influence. $Q_{on}(j, t-1)$ is the entrance volume from on-ramp j during the past minute; $(WF_j)_i$ is the weighting factor of on-ramp j within the area of influence for section i; $Q_{reduction}(i,t) \bullet ((WF_j)_i / \sum_j (WF_j)_i)$ is the volume reduction of on-ramp j because of section i.

The more restrictive of the local rate and the system rate will be selected for further adjustments, including queue adjustment, ramp volume adjustment and advanced queue override. The queue adjustment and advanced queue override are used for preventing traffic spillback onto arterials. Ramp volume adjustment copes with the condition that more vehicles have entered the freeway compared to the number of vehicles assumed to enter, which may be caused by HOV traffic or HOV lane violators. The metering rate to be finally implemented should be within the range of the pre-specified minimum and maximum metering rates.

4.2.3.3 Modeling Adaptive ramp metering algorithms

We have developed these two adaptive ramp-metering algorithms in PARAMICS API on top of loop data aggregation and ramp metering APIs (see Figure 10). The adaptive ramp-metering algorithm API works as the following: at each time increment the advanced algorithm API obtains up-to-date traffic information provided by the loop data aggregator API and historical metering rates provided by ramp metering API, and then sends its computed metering rates to the ramp metering API for implementation. This process of real-time data exchange and the implementation of new control strategy are realized by calling the interface functions of related ITS modules.

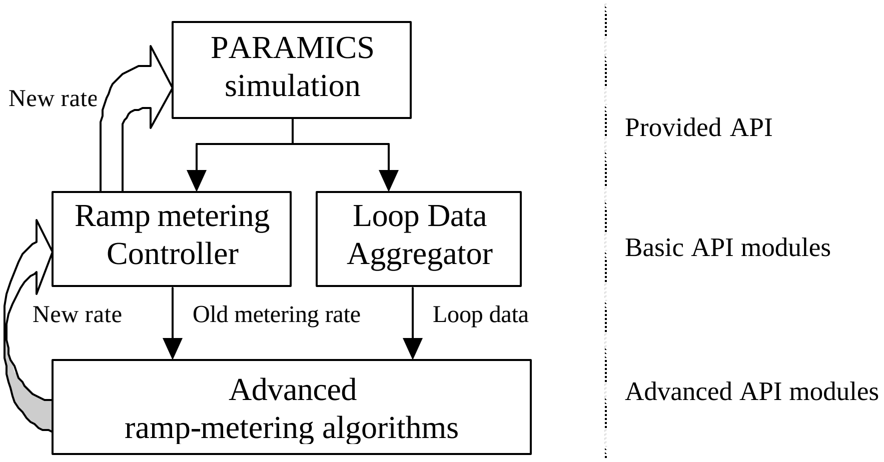

Figure 10 Modeling advanced ramp metering algorithms

4.2.3.4 Calibration of algorithms

Since the incident happens on the northbound I-405, we only apply the ALINEA and BOTTLENECK control to seven on-ramps of the northbound I-405; other on-ramps in the network keep using the current fixed-time control plan. We have calibrated the parameters of these two algorithms over the same section of northbound I-405 freeway in our previous studies (Chu, et al, 2002). The same calibrated parameters for the ALINEA and BOTTLENECK algorithms will be used in this study.

The calibrated parameters of the ALINEA algorithm, shown in Table 4, were obtained based in part on reported practices and on our own calibration experiments on the target network. Since the real-world loop aggregation cycle is 30 seconds, the update cycle is set to 30 seconds in this study in order to quickly feedback the variation of mainline traffic to the ramp control.

Table 4 Calibrated parameters for the ALINEA algorithm

Calibrated parameters	Calibrated values
Location of downstream detector station	60 m
Desired occupancy	20%
Update cycle	30 seconds
Regulation parameter K_R	70 vph

For the BOTTLENECK algorithm, we defined a freeway section as the segment between two adjacent mainline detector stations currently existing in the real world. We also assumed that on-ramps in the area of influence should be within a maximum distance of two miles to the downstream boundary of each section. As a result, there are thirteen sections in the study area. Each section has a pre-defined area of influence, shown in Figure 11. The weighting factors of each on-ramp in the area of influence of each section (shown in Table 5) were calculated based on typical historical demand pattern during the peak hour. In addition, the local control algorithm of BOTTLENECK here uses ALINEA, whose calibration parameters are shown in Table 4.

The metering rates from all above algorithms need to be finally adjusted based on the on-ramp volume restriction, queue override. The on-ramp volume restriction requires the implemented metering rate to be limited within some pre-defined maximum and minimum values. The queue override strategy in our study uses a queue detector located at the ¾ total length of the entrance ramp for detecting excessive queue lengths. As soon as the occupancy of the queue detector exceeds a certain threshold (50% in our study), the metering rate will be set to a maximum value to avoid interference with the traffic on the surface street.

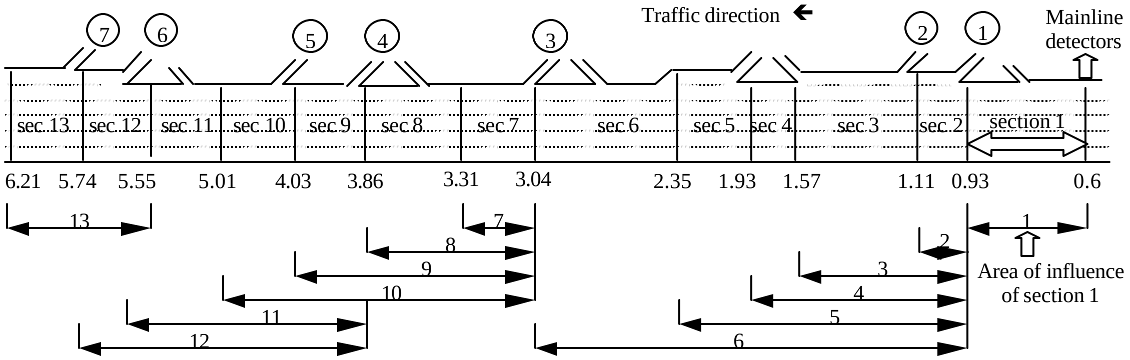

Figure 11 Definition of area of influence for each section in the Bottleneck algorithm

Table 5 Calibrated weighting factors of the Bottleneck algorithm

Section #	Entrance ramp #						
	1	2	3	4	5	6	7
1	1	0	0	0	0	0	0
2	1	0	0	0	0	0	0
3	0.6	0.4	0	0	0	0	0
4	0.6	0.4	0	0	0	0	0
5	0.6	0.4	0	0	0	0	0
6	0.6	0.4	0	0	0	0	0
7	0	0	1	0	0	0	0
8	0	0	1	0	0	0	0
9	0	0	0.8	0.2	0	0	0
10	0	0	0.55	0.1	0.35	0	0
11	0	0	0	0.25	0.75	0	0
12	0	0	0	0.12	0.45	0.43	0
13	0	0	0	0	0	0.37	0.63

4.2.4 Traveler information systems

Scenario 6 considers the involvement of all kinds of traveler information systems, including the VMS and all other information systems from information agencies, but without any traffic control supports. PARAMICS can simulate this scenario by using dynamic feedback assignment, which calculate the resulting route choice based on the instantaneous travel information.

The compliance rate of traveler information, which is the only parameter of this scenario, is set to 5% in this study.

4.2.5 Adaptive signal control

Based on our analysis on the target corridor network, there are two major diversions when an incident happens on the merging area with SR-133 on the northbound I-405. For vehicles from the freeway I-5 to the northbound I-405, the diversion route is to continue to take the northbound I-5 until exiting at off-ramp Alton to westbound Alton Parkway, and then travel to the freeway I-405 at the on-ramp of Sand Canyon. For vehicles from southbound SR-133 and southbound I-5, the diversion route is exiting at the Barranca parkway, going through to the Banting street, turning right to the Alton Parkway and finally entering freeway I-405 at the on-ramp of Sand Canyon.

Given the compliance rate of traveler information, we can further estimate the amount of diverted traffic volume on the two diversion routes based on one simulation run. Then, SYNCHRO, which is a software package for modeling and optimizing traffic signal timings, is used to off-line optimize the signal control along diversion routes during the incident period. The optimized signal timing plans will be applied when the integrated control strategy is activated because of incidents.

4.2.6 Combination

Scenario 7 and 8 implement the so-called integrated control strategy, which involves the use of traffic routing (caused by all kinds of traffic information systems), adaptive signal control and ramp metering together during the incident period. Compared scenario 7 and 8, scenario 8 uses ALINEA ramp-metering control instead of the fixed-time metering applied in scenario 7.

The detailed integrated control strategy applied here is described as follows: five minutes after the occurrence of the incident, the freeway operation agency and arterial management agency activate the new control schemes, including showing diversion messages on six related VMS, applying new signal timing plans to traffic signals along diversion routes, and increasing ramp metering rate at the entrance ramp at Sand Canyon where most diverted vehicles enter the northbound of freeway I-405. At the same time, traffic information systems also report the occurrence of the incident and provide a shortest path for users.

5 SIMULATION RESULTS AND ANALYSIS

5.1 Performance measures

The purpose of evaluation studies is to use some overall performance measures to evaluate how the implementation of an ITS strategy benefit the whole traffic system, including the freeway and arterial part of the network. The following measures of effectiveness (*MOE*s) are used to evaluate the effectiveness of each ITS strategy in this paper. The performance measure API is responsible for the computing, gathering and reporting these measures.

MOE #1 system efficiency measure: average system travel time (ASTT) of the whole simulation period. ASTT is calculated as the weighted mean of the average travel times of all OD pairs

$$ASTT = \sum_{\forall i,j} (T_{i,j} \bullet N_{i,j}) \Big/ \sum_{\forall i,j} N_{i,j} \tag{10}$$

where $N_{i,j}$ is the total number of vehicles that actually traveled from origin i to destination j; $T_{i,j}$ is the average OD travel time from origin i to destination j;

MOE #2 system reliability measure: average standard deviation of OD travel times (Std_ODTT) of the whole simulation period. Std_ODTT is calculated as the weighted standard deviation of the average travel times of all OD pairs for the whole study period:

$$Std\_ODTT = \sum_{\forall i,j} (Std(T_{i,j}) \bullet N_{i,j}) \Big/ \sum_{\forall i,j} N_{i,j} \tag{11}$$

where $Std(T_{i,j})$ is the standard deviation of the average OD travel time from origin i to destination j.

MOE #3 freeway efficiency measure
  (1) average mainline travel speed of the entire simulation period (AMTS)
  (2) average mainline travel speed during the congestion period (peak_AMTS). The congestion period is defined as the congestion period of the baseline scenario.

MOE #4 on-ramp efficiency measure
  (1) total on-ramp delay (TOD)
  (2) time percentage of the on-ramp queue spillback to the local streets (POQS)

MOE #5 arterial efficiency measure
  (1) average travel time from the upstream end to the downstream end of an arterial (ATT)
  (2) the standard deviation of ATT (std_ATT)

5.2 Determination of number of simulation runs

PARAMICS is a stochastic simulation model, which rely upon random numbers to release vehicles, select vehicle type, select their destination and their route, and to determine their behavior as they move through the network. Therefore, the average results of several simulation runs using different seed number can reflect the traffic condition of a specific scenario.

In order to determine the number of simulation model runs, we need to know the variance of a number of performance measures from simulation results, which are unknown before simulations The flow chart to determine the number of simulation runs is shown in Figure 12.

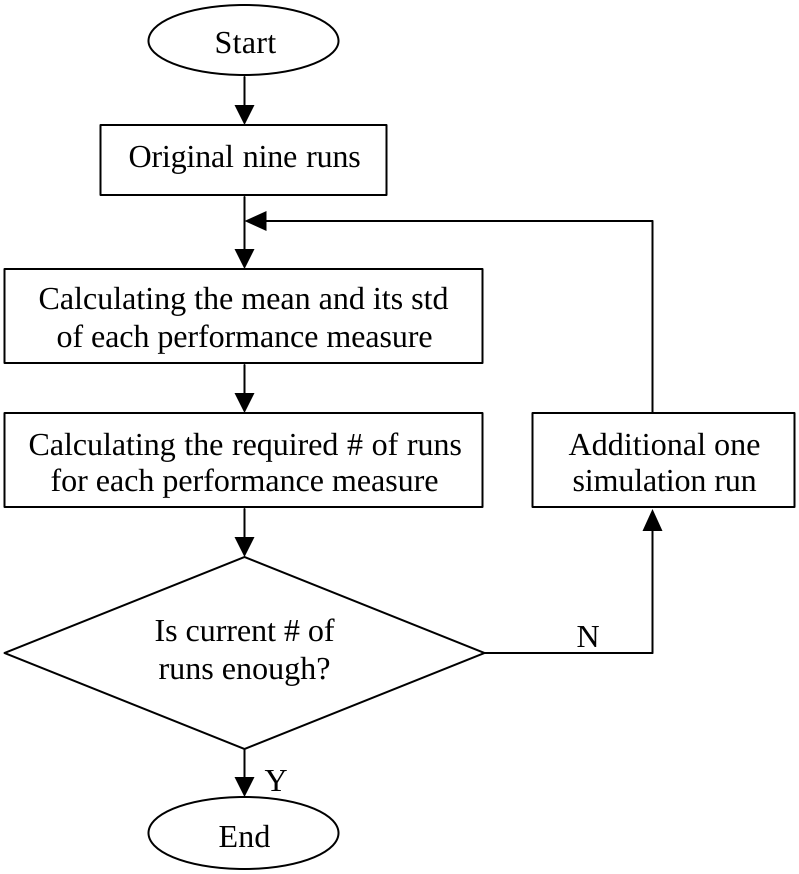

Figure 12 Flow chart of the determination of number of simulation runs

We execute nine simulation runs first and then calculate the number of runs needed according to the mean and standard deviation of a performance measure of these nine runs:

$$N = (t_{a/2} \bullet \frac{d}{m \bullet e})^2 \qquad (12)$$

where µ and d are the mean and standard deviation of the performance measure based on the already conducted simulation runs; e is the allowable error specified as a fraction of the mean µ; $t_{a/2}$ is the critical value of the t-distribution at the confidence interval of a. This calculation needs to be done for all performance measures of interest. The highest value from variances is the required number of runs. If the current number of runs is already larger than this value, the simulation of this scenario is ended. Otherwise, one additional run is performed and then the required number of runs needs to be recalculated.

5.3 Evaluation results

There are eight evaluation scenarios. The simulation time periods in all scenarios are morning peak hours from 5:45 to 10:00 a.m. The first fifteen minutes of each simulation run are treated as the "warm-up" period. All control scenarios are compared with the no incident management scenario, i.e. Scenario 1.

The number of simulation runs for each scenario is determined by the method described in section 5.4.2. Due to the purposes of this study, we select two measures, the average system travel time and the average mainline travel speed during the congestion period, for the calculation of the required number of runs. Based on multiple runs, the value of each performance measure for a scenario is equal to the average value of all simulation runs of the scenario.

The overall performance measures, including the system efficiency measure and system reliability measure are shown in Table 6 and Figure 13 and 14. The performance of the northbound freeway I-405, where the incident happened, is shown in Table 7 and Figure 15. Table 8 shows the performance of the arterials. The evaluation results show that all ITS strategies have positive effects on the improvement of network performance. In addition, if more ITS components involved, more benefits can be obtained, as shown in Figure 16.

Incident management (Scenario #2 and #3) can improve system performance because it effectively increases the average mainline travel speed during the congestion period and the whole study period on the northbound I-405, as shown in Figure 17, which compares the freeway mainline speed variation over time under these three incident management scenarios. Therefore, fast incident response is of particular importance to freeway traffic management and control. In order to achieve this, comprehensive freeway surveillance system and automatic incident detection are both required.

Theoretically, adaptive ramp metering (Scenario #4 and #5), which can adjust metering rate based on the traffic condition of mainline freeway, can benefit vehicles that are already on the freeway. However, based on our simulation results, we find the performance improvement introduced by adaptive ramp metering is minor under the incident scenarios. Both ALINEA and BOTTLENECK cannot improve system travel time or freeway travel speed significantly. This can be seen from Figure 18, which shows the variation of the mainline freeway travel speed over time under scenarios of existing incident management. This explains that if the congestion becomes severe, the target level of service (LOS) could not be maintained by using ramp metering and the effectiveness of ramp control is marginal. In addition, adaptive ramp metering performs worse than the improved incident management scenario, which means shorter incident clearance time can generate more benefits than a complex adaptive ramp metering under the non-recurrent congestion.

Comparing these ramp-metering controls (Scenario #4 and #5), the coordinated ramp metering control, i.e. BOTTLENECK, performs a little bit better than the local adaptive ramp-metering control, ALINEA. The reason is that BOTTLENECK can response to not only the local congestion but also the congestion appeared in a coordinated area. Both of ALINEA and BOTTLENECK imposes a certain amount of delay on vehicles from entrance ramps. ALINEA performs better than BOTTLEENCK in the aspect of less total on-ramp delay and less probability of vehicles on the entrance ramps spillback to the surface streets. Due to the coordination feature of BOTTLENECK, it causes the highest total on-ramp delay.

Scenarios #6, #7 and #8 not only improve the system efficiency but also increase the system reliability significantly. All these three scenarios involve real-time traveler information systems. The finding here demonstrates that traveler information systems can greatly improve the overall system performance if they are deployed properly. Also, because of the network topology -- one major freeway segment (I405) with two parallel arterial streets (ALTON and BARRANCA), real-time traveler information system can divert traffic from congested freeway to arterial streets, therefore has the greater benefits than adaptive ramp metering algorithms (Scenario #4 and #5) and improved incident management (Scenario #3).

Scenario #7 tries to integrate traveler information with traffic control. Unlike Scenario #6, the traffic signal control and ramp metering in scenario #7 are adjusted to facilitate the diversion of traffic. An updated signal timing plan and non-metering scheme are applied to related signals and ramp meters along the diversion routes during the period of corridor control, which may lead to shorter travel time along diversion routes, as shown in Table 8. The second combination scenario (#8) can be regarded as a better version of integrated control, which has the involvement of ALINEA ramp-metering control. It shows the best performance among all scenarios. It generates more benefits to the average system travel time, average mainline travel speed though it also introduces a little bit more on-ramp delays than the corridor control scenario.

Base on Figure 16, 17 and 18, time period between 8:05 and 8:20 is always the worst time of traffic congestion. The implementation of any ITS strategy in this study cannot help avoid and improve the worst time. This result is reasonable for the incident management scenarios and adaptive ramp metering scenarios because they do not involve traffic diversion. For scenarios #6, #7, and #8, in which traffic diversion has been involved, there are two reasons that can explain this result. Firstly, the traffic assignment method of PARAMICS, i.e. dynamic feedback assignment, is used for the calculation of the shortest path based on instantaneous travel time information feedback from simulation. The feedback interval was set to 60 seconds in our study. When the alternative route (i.e. arterials) can save more travel time compared to the old route (i.e. freeway), vehicles will use the alternative. Some time is needed to satisfy this condition because the alternative route actually has longer physical distance and many signalized intersections. Secondly, we considered the response time of incident in our study. It takes five minutes for traffic control facilities in scenarios #7 and #8 to apply the adaptive signal timing plans under incident condition. On the other hand, because of the involvement of traffic diversion, scenario #6, #7 and #8 clearly "recovers" faster than the baseline scenario #1 (maybe as much as 15-30 minutes faster).

Our findings from the above analysis can be summarized briefly as follows. Firstly, real-time traveler information systems have the strong positive effects to the traffic systems. Secondly, adaptive ramp metering cannot improve the system performance effectively under incident scenario. Thirdly, fast incident response is important to the performance improvement. Finally, proper combination of ITS strategies yields greater benefits.

Table 6 Overall performance of each strategy

Control strategy	ASTT (sec)	ASTT Saving (%)	std_ODTT (sec)	Reliability Increase (%)
Baseline	271.3		51.7	
IM-33	297.0	0.0%	139.6	0.0%
IM-26	293.9	1.0%	130.7	6.4%
IM-22	289.1	2.7%	112.6	19.4%
ALINEA	289.7	2.4%	118.9	14.9%
BOTTLENECK	289.2	2.6%	115.5	17.3%
TI	284.4	4.2%	95.3	31.8%
Corridor control	280.5	5.5%	93.2	33.3%
Combination	279.6	5.9%	97.2	30.4%

Notes: ASTT – Average system travel time

Std_ODTT— Average standard deviation of OD travel times of the entire simulation period, which represents the reliability of the network

Table 7 Performance of the northbound of freeway I-405

Scenario	AMTS (mph)	AMTS Increase (%)	peak_AMTS (mph)	Increase of peak_AMTS	TOD (hour)	POQS (%)
Baseline	57.3		50.1		55.1	1.8%
IM-33	50.5	0.0%	37.2	0.0%	55.6	1.9%
IM-26	51.4	1.8%	39.4	6.0%	54.6	2.0%
IM-22	51.9	2.8%	40.0	7.5%	54.0	1.8%
ALINEA	51.6	2.1%	39.8	6.9%	57.6	0.9%
BOTTLENECK	51.9	2.7%	39.7	6.7%	89.1	1.9%
TI	51.9	2.8%	39.9	7.3%	58.0	1.8%
Corridor control	52.2	3.3%	41.0	10.1%	59.5	1.9%
Combination	52.3	3.5%	40.6	9.1%	60.0	1.0%

Notes: AMTS – Average mainline travel speed of entire simulation period (6 – 10 AM)
peak_AMTS – Average mainline travel speed of congestion period (7:30 – 9:30)
TOD – Total on-ramp delay
POQS – Time percentage of vehicles on the entrance ramps spillback to the surface streets

Table 8 Performance of arterials (Alton Parkway)

Scenario	Westbound ALTON		Eastbound ALTON	
	ATT (sec)	std_ATT	ATT (sec)	std_ATT
Baseline	515.8	70.3	450.4	54.5
IM-33	515.5	71.0	451.7	53.8
IM-26	514.1	68.1	451.7	54.6
IM-22	512.4	68.1	450.5	55.1
ALINEA	513.6	67.3	450.0	53.8
BOTTLENECK	518.3	69.0	450.5	54.7
TI	518.8	70.2	453.5	56.8
Corridor control	423.5	51.4	447.5	54.2
Combination	423.2	51.0	446.5	55.1

Notes: ATT – Average travel time
Std_ATT – Standard deviation of the average travel time

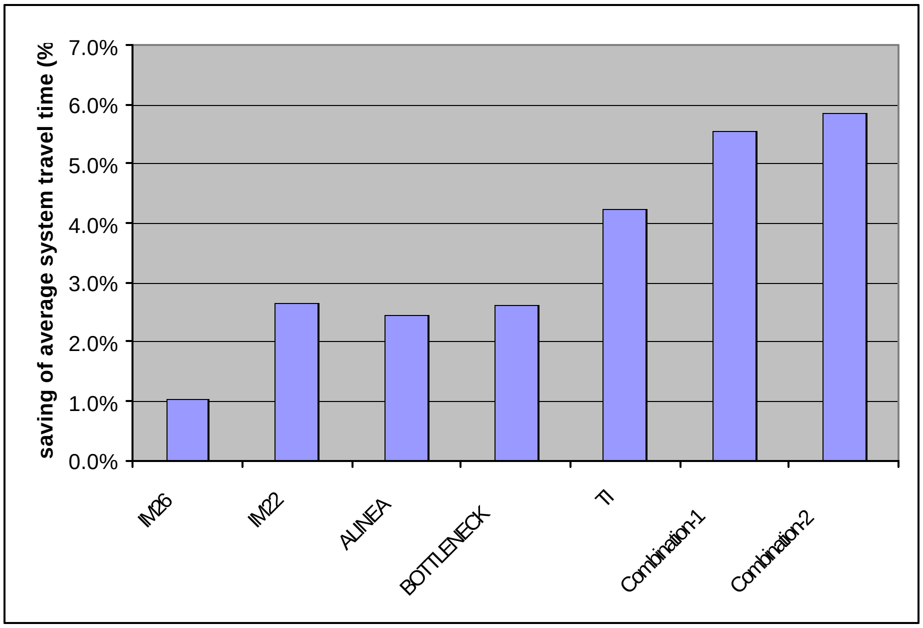

Figure 13 Comparison of the saving of average system travel time

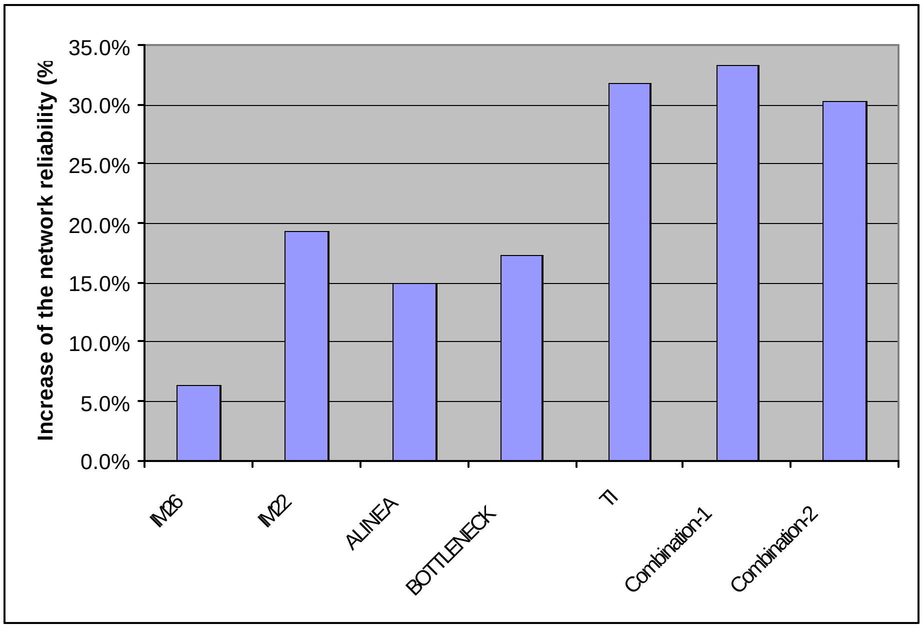

Figure 14 Comparison of the increase of the network reliability

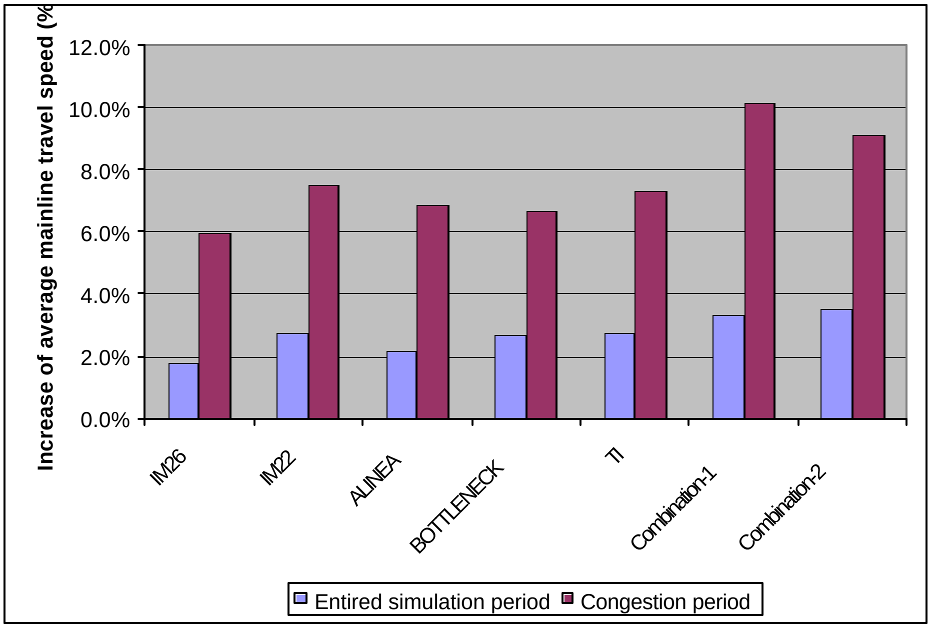

Figure 15 Comparison of the increase of average mainline travel speed of the northbound I-405 during the congestion period (7:30 - 9:30 AM) and the entire simulation period (6:00 - 10:00 AM)

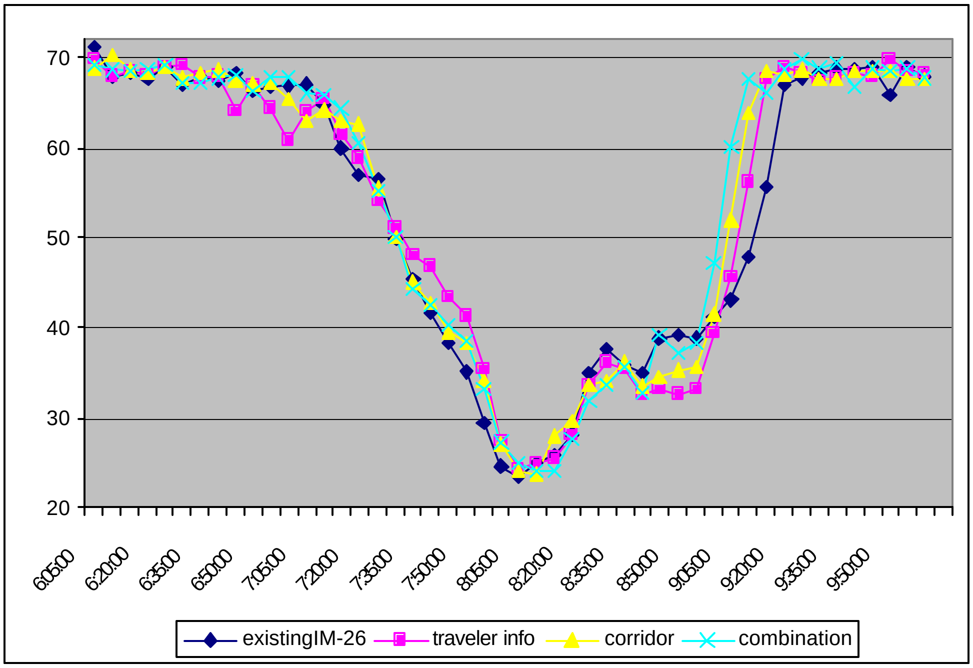

Figure 16 Comparison the freeway mainline speed (unit: mph) variation over time under scenarios with traveler information

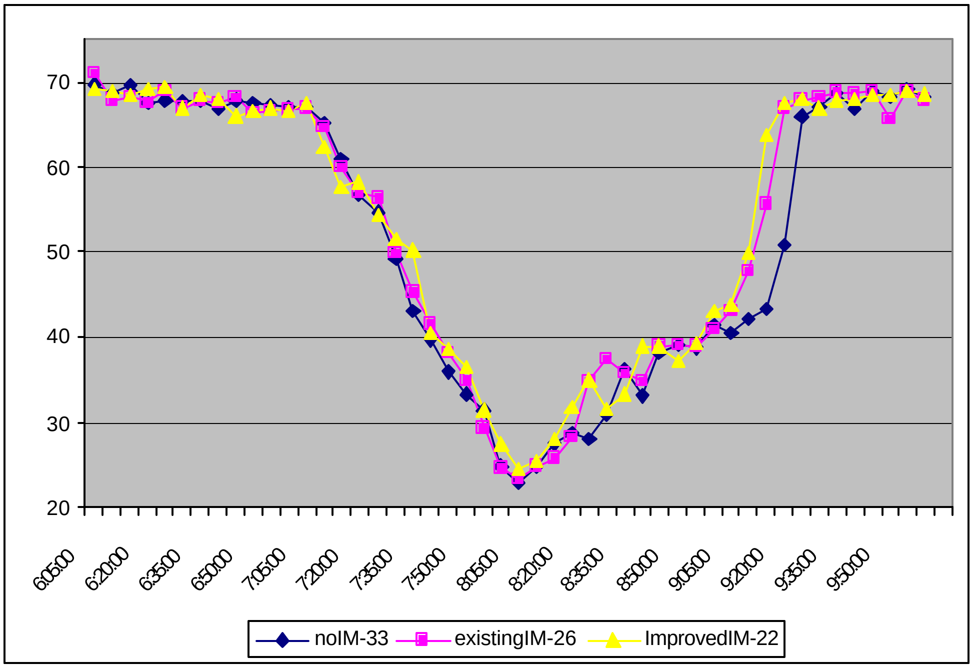

Figure 17 Comparison the freeway mainline speed variation (unit: mph) over time under incident management scenarios

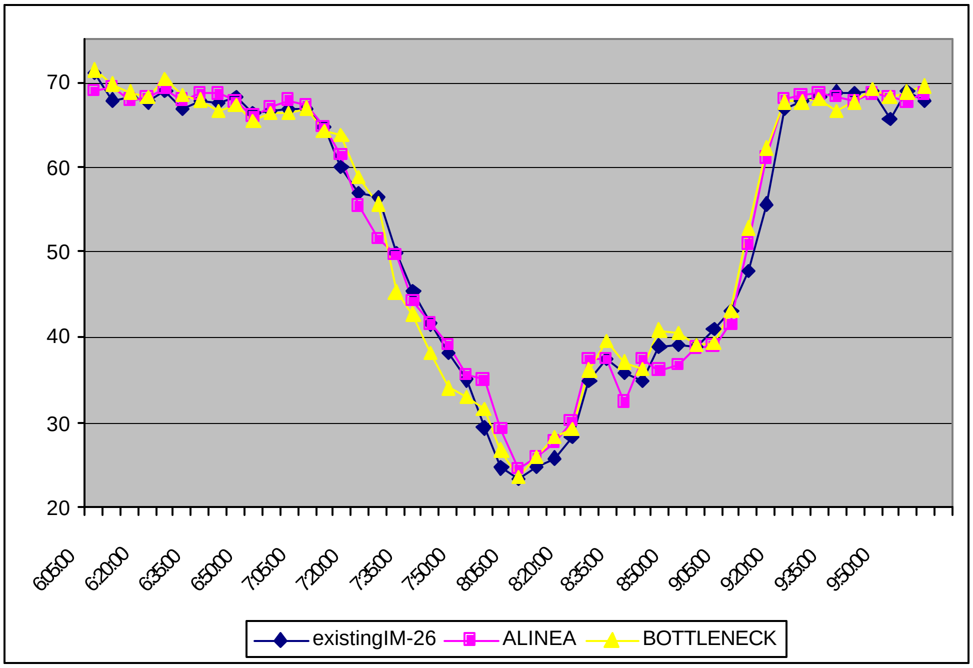

Figure 18 Comparison the freeway mainline speed (unit: mph) variation over time under adaptive ramp metering scenarios

6 CONCLUSIONS

This report presents a micro-simulation method to evaluate the effectiveness of potential ITS strategies. A capability-enhanced PARAMICS micro-simulation environment is established by integrating various plug-in modules through Application Programming Interfaces in order to model the current traffic conditions and various potential ITS strategies.

The simulation-based evaluation study involves many technical details if applying to a real network in order to obtain quantitative evaluation results. The procedures of how to evaluate ITS strategies in the enhanced PARAMICS have been demonstrated. We use a practical method to calibrate a studied corridor network, which includes three freeways and several major arterials. Based on this calibrated model network, we evaluated the effectiveness of a number of potential ITS strategies under a non-recurrent incident scenario. The evaluated ITS strategies include incident management, local adaptive ramp metering and coordinated ramp metering, traveler information systems, corridor control, and the combination of traveler information systems, corridor control and adaptive ramp metering. These ITS strategies were implemented and evaluated in the enhanced PARAMICS environment. Performance measures include the efficiency of the overall system, mainline freeway, on-ramp, and arterials and the reliability of the network. The evaluation results show that all ITS strategies have positive effects on the improvement of network performance. If applying only one single ITS strategy, the adaptive ramp metering and incident management are not effective compared with real-time traveler information. The combination of several ITS components, such as the corridor control, and the combination scenarios, can generate the better benefits.

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