Paper No. 02-3427

Development of A Simulation Laboratory for Evaluating Ramp Metering Algorithms

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Submitted to 2002 TRB Annual Meeting

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ABSTRACT

As an efficient traffic control strategy to ameliorate freeway traffic congestion, ramp metering has been successfully applied in the US. However, the applicability and effectiveness of a ramp-metering strategy are required to be investigated during the pre-implementation phase in order to ensure the success of the implementation. The use of traffic simulation models can provide a quick and cost-effective way to test and evaluate a ramp-metering algorithm prior to implementation on the freeway network. In this paper, a micro-simulation laboratory, based on a functionality-enhanced PARAMICS simulation model through integrating some complementary ATMIS modules, has been established for the evaluation study of ramp metering control. Three adaptive ramp metering algorithms, including ALINEA, BOTTLENECK and ZONE, have been evaluated in this PARAMICS simulation laboratory over a stretch of freeway I-405, California. Simulation results show that the two coordinated ramp-metering algorithms, i.e. BOTTLENECK and ZONE, perform better than the current fixed-time control and ALINEA algorithm under both morning and afternoon scenarios.

1. INTRODUCTION

With increased travel demands, freeways have experienced or will face increasingly congested traffic. Ramp metering, aimed at limiting access to the freeway mainstream in order to achieve and maintain capacity flow and either avoid or ameliorate traffic congestion, has been recognized as an effective freeway management strategy. An estimated 2,500 ramps are currently being metered in 21 metropolitan areas in the U.S. and also in many other countries of the world *(1)*. Modes of metering operation can be divided into three primary categories: fixed-time, local traffic responsive, and coordinated traffic responsive. A fixed-time ramp-metering plan is based on historical traffic information and established on a time-of-day basis. For local traffic responsive operation, the metering rate is based on prevailing traffic conditions in the vicinity of the ramp. Coordinated traffic responsive ramp metering operation seeks to optimize a multiple-ramp section of a highway, often with the control of flow through a bottleneck as the ultimate goal.

A variety of ramp metering algorithms have been proposed and implemented based on optimization techniques *(2)*, automatic control *(3,4)*, optimal control theory *(5)* or artificial intelligence methods including fuzzy, rule-based expert systems and neural networks *(1,6)*. Though significant theoretical developments have been achieved, their implementations have been slow in coming. Most existing ramp meters in the field are fixed-timed control or demand-capacity control *(3)*. Recently, advanced coordinated traffic-responsive ramp metering strategies began to be deployed, and are regarded as the most promising control strategy for the future *(7)*. Notable instances of coordinated ramp-metering algorithms currently deployed include the ZONE algorithm in Minneapolis / St. Paul, Minnesota *(8)*, BOTTLENECK algorithm in Seattle, Washington *(9)*, HELPER algorithm in Denver, Colorado *(10)*, METALINE in Paris and Amsterdam *(2,11)*, SDRMS in San Diago, California, SWARM in Orange County, California *(12)*. Because of the complexity of these coordinated ramp metering systems, their successful implementation depends both on hardware or ITS infrastructure (such as communication system and loop detectors installed at specific locations), and software (such as the design and operational calibration of a ramp metering algorithm).

Ramp metering control involves balancing the interests of local (arterial) travelers and through (freeway) traffic, and thus, its applicability, onsite deployment and operation continue to face political challenges and need the cooperation of related parties. Facts show that significant benefits can be obtained from ramp metering only when implemented correctly and operated effectively *(13)*. Therefore, whether ramp metering is fit to the local traffic condition, which kind of ramp metering algorithms is suitable and how to calibrate and optimize operational parameters accordingly, are required to be investigated during the pre-implementation phase in order to ensure the success of the implementation.

There are two ways to evaluate the performance of ramp metering systems, field operational tests and computer simulations. The field tests are very expensive and time-consuming; only a few evaluation reports are available currently *(11,14,15)*. Alternatively, there have been a number of simulation studies on ramp metering algorithms; examples of such have used INTEGRATION and CORSIM for testing time-of-day control *(16)*, METANET and CORSIM for testing ALINEA and METALINE algorithms *(2,3)*, and MITSIM for testing ALINEA and FLOW algorithms *(17)*. Although the field tests provide the ultimate fair evaluation of the actual performance when applied in the real world, it may be affected by some uncontrollable factors. The simulation-based evaluation can be used for the design or pre-implementation phase, but may be influenced by theoretical limitations inside simulation models.

Traffic simulation models can be classified as being either microscopic, mesoscopic, or macroscopic according to their representation of traffic flow (or vehicle movement). Microscopic models, such as PARAMICS, CORSIM, VISSIM, AIMSUN2, TRANSIM and MITSIM, continuously or discretely calculate and predict the state of individual vehicles, and measure the speed and location of each individual vehicle in the simulation. Macroscopic models, such as FREFLO, AUTOS, METANET and VISUM, aggregate the description of traffic flow to speed, flow, and density of each link in the network. Mesoscopic models, such as DYNASMART, DYNAMIT, INTEGRATION and METROPOLIS, have aspects of both macroscopic and microscopic models. These models have been applied successfully to particular studies, but their applications are relatively limited. Most are designed for particular applications and useful only for specific purposes, missing some components of Advanced Transportation Management and Information Systems (ATMIS). Microscopic simulators, which do not depend on theoretical traffic flow models but on vehicle-vehicle interactions, are deemed more appropriate for evaluating ramp-metering algorithms, and other ATMIS strategies *(18)*.

This paper is organized as follows. Section 2 presents an overview of California PATH ATMS Testbed, the introduction of the simulation model used in this study - PARAMICS, and the efforts on enhancing functionalities of PARAMICS through developing some complementary modules in PARAMICS API. Section 3 describes the ramp-metering algorithms to be evaluated, including ALINEA, BOTTLENECK, and ZONE algorithms. In section 4, these algorithms were tested and evaluated over a stretch of the I-405 freeway in California, in the functionality-enhanced PARAMICS simulation laboratory. Simulation results and discussion are given in Section 5. Finally, concluding remarks are presented in Section 6.

2. FRAMEWORK OF SIMULATION LABORATORY

2.1 California PATH ATMS Testbed

The California PATH ATMS Testbed located at UC-Irvine provides an instrumented, multi-jurisdictional, multi-agency transportation operations environment linked to university laboratories for real-world development, testing and evaluation of near-term technologies and ATMIS applications, and to serve as an ongoing testing ground for California and national ITS efforts. Through ATM communication network, the testbed currently has direct links to three traffic operation centers: Caltrans District 12 Traffic Management Center, City of Anaheim Traffic Management Center, and City of Irvine Transportation Research Analysis and Control Center. Real-time loop data are received at the testbed and then stored in the Oracle database. A general goal of the testbed is to develop and maintain an implementation platform that gives testbed researchers "plug and play" capabilities with rich and various traffic data, ATMIS modules and sub-systems.

A microscopic traffic simulator, PARAMICS, is integrated to the testbed development environment. The prime objective of using traffic simulators in the ATMS Testbed is to serve as both an off-line evaluation/design tool and an on-line control/guidance tool for dynamic transportation management.

2.2 Micro-simulator: PARAMICS

As a suite of ITS-capable, user-programmable, high-performance microscopic traffic simulation package, PARAMICS offers very plausible detailed modeling for many components of an ‘ideal’ simulator. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing accurate traffic flow, transit time and congestion information, as well as enabling the modeling of the interface between drivers and ITS facilities. In addition, PARAMICS provides users with an Application Programming Interface (API) through which users can customize and extend many features of the underlying simulation model. Based on provided API functions, users can further develop an external or complementary module, or their own API functions to implement or test an ITS application without having to deal with the underlying proprietary code. Therefore, such an API has a dual role,

- to allow researchers to override the simulators default models, such as car following, lane changing, route choices for instance, and
- to allow them to interface complementary or external modules to the simulator.

Complementary modules could be any ITS application, such as signal optimization, adaptive ramp metering, incident management and so on. In this way, new control strategy can be easily tested and evaluated by the simulator before their implementation in the real world.

PARAMICS excels in modeling congested networks and ITS infrastructures *(19)*. The ability of PARAMICS to simulate the real-world traffic has been shown by former efforts on the model calibration and validation of PARAMICS using California data *(20,21)*. Some complementary ATMIS modules, including actuated signal controller Type 170, coordinated actuated signal controller Type 2070, time-based ramp meter controller, have been developed for the simulation laboratory, at the UCI ATMS Testbed *(22)*.

2.3 Simulation Laboratory

The simulation laboratory is a functionality-enhanced PARAMICS simulation environment that can be used for ATMIS research. Figure 1 illustrates the framework of the simulation laboratory for evaluating ramp metering algorithms. In the simulation laboratory, some complementary ATMIS modules, including time-based ramp controller, loop data aggregator and measures of effectiveness (MOE) API, are developed in PARAMICS API for enhancing functionalities of PARAMICS in order to fit to the need of this study. Those evaluated ramp-metering algorithms are coded in PARAMICS API and work in the simulation laboratory as external modules.

The time-dependent travel demands are derived from planning demand data and real-world loop data stored in the Oracle database in the testbed. The time-based ramp module is the ramp signal controller, which provides interface functions used for querying the current metering rate and setting a new metering rate to any a specific ramp meter. The module of the loop data aggregator is developed in order to emulate the real-world data collection from induction loop detectors. During the simulation process, MYSQL database can be used for storing intermediate results, such as aggregated loop data. The MOE API is used for the calculation and output of performance measures of each metering control.

3. RAMP METEING ALGORITHMS

Although a large body of theoretical development and practical algorithms on ramp metering is available, the ramp-metering algorithms used for this evaluation study are three representative adaptive algorithms, including one local traffic-responsive algorithm, ALINEA, and two coordinated algorithms: BOTTLENECK algorithm of Washington

State and ZONE algorithm of Minnesota. These algorithms are briefly described in this section.

3.1 ALINEA Algorithm

The ALINEA algorithm, proposed by Papageorgiou et al *(2,3)*, is a local feedback ramp metering policy. The algorithm attempts to maximize the mainline throughput through maintaining a desired (or optimal) occupancy on the downstream mainline freeway. The metering rate of time interval *t* is calculated based on the following formula:

$$r(t) = \tilde{r}(t-1) + K_R \bullet (O_{desired} - O_{downstream}(t)) \quad (1)$$

where $O_{desired}$ is the desired occupancy of the downstream detector station; $O_{downstream}(t)$ is the measured occupancy at the downstream detector station; $\tilde{r}(t-1)$ is equal to the measured on-ramp volume for time interval $t -1$, and K_R is a regulator parameter.

Therefore, the implementation of the ALINEA algorithm requires two detector measurement stations, one on the mainstream, immediately downstream of the ramp, and the other one on the entrance ramp.

3.2 BOTTLENECK Algorithm

The BOTTLENECK algorithm has been applied in Seattle, Washington for several years *(9)*. In the algorithm, the freeway segment under study is divided into several sections for the calculation of system-level metering rate. A freeway section is defined by the stretch of freeway between two adjacent mainline detector stations.

The algorithm can generate a local-level metering rate and a system-level metering rate. The local-level metering rate is selected from a predetermined look-up table of metering rates, on the basis of occupancy levels upstream of the metered ramp. The system-level or bottleneck metering rate is calculated on the basis of system capacity constraints. This algorithm is activated when the following two conditions are met:

1. Capacity condition

$$O_{downstream}(i,t) \geq O_{threshold}(i) \quad (2)$$

where $O_{downstream}(i, t)$ is the average occupancy across the downstream detectors of section *i* over the previous 1-minute period, and $O_{threshold}(i)$ is the occupancy threshold for the downstream detector of the section *i* when it is operating near capacity.

2. Vehicle storage condition

$$Q_{upstream}(i,t) + Q_{onramp}(i,t) \geq Q_{offramp}(i,t) + Q_{downstream}(i,t) \quad (3)$$

where $Q_{upstream}(i, t)$ is the volume entering section i across the upstream detector stations during the last minute; $Q_{onramp}(i, t)$ is the volume entering section i during the last minute from on-ramps; $Q_{offramp}(i, t)$ is the volume exiting section i during the last minute to off-ramps; $Q_{downstream}(i, t)$ is the volume exiting section i across the downstream detector stations during the last minute.

The upstream ramp volume reduction $Q_{reduction}(i, t)$ is equal to the number of vehicles stored in the section during the past minute:

$$Q_{reduction}(i,t) = (Q_{upstream}(i,t) + Q_{onramp}(i,t)) - (Q_{offramp}(i,t) + Q_{downstream}(i,t)) \quad (4)$$

Each section has an area of influence that includes several upstream ramps. These ramps are responsible for the volume reduction for a given section on the basis of a set of weighting factors, which are defined according to how far it is to the downstream detector station and the demand level of the ramp. The bottleneck metering rate will be equal to:

$$r(j,t) = Q_{onramp}(j,t-1) - \underset{i=1}{\overset{n}{MAX}}\left(Q_{reduction}(i,t) \bullet \frac{(WF_j)_i}{\sum_j^n (WF_j)_i}\right) \quad (5)$$

where $r(j, t)$ is the bottleneck metering rate for ramp j, $Q_{onramp}(j, t-1)$ is the entrance volume on ramp j during the past minute, $(WF_j)_i$ is the weighting factor of ramp j within the area of influence for section i, $Q_{reduction}(i,t) \bullet \frac{(WF_j)_i}{\sum_j^n (WF_j)_i}$ is the volume reduction of ramp j because of section i, n is the total sections in the network, $\underset{i=1}{\overset{n}{MAX}}$ is the operator of selecting the maximum volume reduction if a ramp is inside of multiple areas of influences.

The more restrictive ramp rate of the local rate and bottleneck rate will be selected for further adjustment, including queue adjustment, ramp volume adjustment, advanced queue override. The queue adjustment and advanced queue override are used for preventing spillback onto the arterial network. Ramp volume adjustment copes with the condition that more vehicles have entered the freeway compared with the number of vehicles supposed to enter, which may be caused by HOV lanes or violators. The adjusted metering rate should be within the restriction of the pre-specified minimum and maximum metering rate.

3.3 ZONE Algorithm

The ZONE algorithm has been successfully applied in Minneapolis/St. Paul area, Minnesota *(8)*. This algorithm divides a directional freeway into zones, which have a variable length of 3 to 6 miles and may contain several metered or non-metered on-ramps and off-ramps. The upstream end of a zone is a free-flow area and the downstream end of a zone generally is a critical bottleneck. The system-level metering rate is determined by volume control of each zone. The basic concept of the algorithm is to balance the volume of traffic entering the zone with the volume of traffic leaving the zone. The metering zone equation is:

$$M + F = X + B + S - (A + U) \tag{6}$$

Where M and F are controlled variables. M is the total metered ramp volumes, F is the total metered freeway to freeway ramp volumes; A is the measured upstream mainline volume; U is the total measured non-metered ramps volume; X is the total measured off-ramp volumes; B is the downstream bottleneck volumes at capacity, which is set to 185 vehicles per lane per 5 minutes; S is the space available within the zone, which can be calculated based on an experimental formula that considers measured occupancy values of mainline detectors inside the zone.

Each ramp also has a local-level metering rate, determined based on an occupancy control strategy. The detectors of up to three miles downstream of each ramp are accounted for the possible downstream bottleneck.

Based on historical peak-hour loop counts and the above metering zone equation ($S = 0$), a ramp rate lookup table is made with 6 distinct metering rates for each ramp. Each rate also corresponds to a certain occupancy threshold of downstream detector stations for the occupancy control purpose. The more restrictive metering rate of the volume control rate and the occupancy control rate is always selected for operation.

4. EVALUATION STUDY

4.1 Study Site and Data Acquisition

The study site is a 6-mile stretch of northbound freeway I-405, between the junction of I-405 and I-5 and Culver Dr, in Orange County, California. The network has seven on-ramps, four off-ramps and one freeway to freeway ramp connecting I-405 with SR-133, which is un-metered. The schematic representation of the study site is illustrated in Figure 2. The lines across the freeway lanes represent mainline detectors, whose locations are shown on the bottom by post-miles. There are also detectors located on entrance and exit ramps, which are not shown in the figure.

As a major freeway linking Orange County and Los Angeles, I-405 experiences heavy traffic everyday. During the morning peak hour from 6:00 to 9:00 a.m. and afternoon peak hour from 3:00 to 6:00 p.m., the vehicle-actuated fixed-time ramp control is currently applied on ramps based on a one-car-per-green principle in this section.

The time-dependent OD demands are derived based on the planning OD demands and the real-world loop data with 30-second time interval, which can be obtained at the PATH ATMS Testbed. The travel demand data of Feb. 22, 2001 was used for model calibration. Travel demand data from Jan. 15, 2001 to Jan. 19, 2001 were regarded as historical data in this study for the calibration of operational parameters of ramp-metering algorithms. The demand data of Feb. 23, 2001 was used for evaluation.

4.2 Measures of Effectiveness

The following measures of effectiveness (*MOE*s) are used to evaluate ramp-metering algorithms in this paper. The *MOE* module in the simulation laboratory calculates and outputs these measures.

(1) Generalized total vehicle travel time (*GTVTT*), which is a measure of system performance for the whole network. All vehicles, including those having finished their journey and those currently simulated, are all considered in this measure. This measure can be formulated as follows:

$$GTVTT = \sum_{\forall i,j} D_{i,j} \bullet \left(\sum_{k=1}^{N_{i,j}} T_{i,j}^{k} \Big/ N_{i,j} \right) \tag{7}$$

where

$N_{i,j}$ = the total number of vehicles that actually traveled between origin *i* and destination *j*,
$D_{i,j}$ = the travel demand from origin *i* to destination *j* for the whole simulation time, and
$T_{i,j}^{k}$ = the travel time of the *k*th vehicle that traveled origin *i* to destination *j*.
Note the reason to use *GTVTT* is that $D_{i,j}$ is not equal to $N_{i,j}$ because of the randomness of the micro-simulation.

(2) Average mainline travel time (*AMTT*), which is used for evaluating the overall traffic condition on the mainline freeway.

(3) Average on-ramp waiting time (*AOWT*), which is a measure evaluating the effect of ramp control to the traffic flow on entrance ramps.

(4) Average OD travel time (*AODTT*), which considers the average travel time for vehicles between a specific OD pairs. Note that we use this measure to evaluate the effect of control on vehicles from an entrance ramp to the downstream end of the freeway.

The last three measures can be aggregated over either a certain time interval or the whole simulation period.

4.3 Calibration of PARAMICS

Micro-simulation models need to be calibrated carefully before being applied to a specific research. PARAMICS Build 3.0.7 is used in our study. PARAMICS regards each vehicle in the simulation as a Driver Vehicle Unit (DVU), and thus simulation relies on characteristics of drivers and vehicles, the interactions between vehicles, and network geometry as well.

Some efforts have been put to the calibration of PARAMICS *(20,22,23,24)*. Our calibration study include the following details:

(1) Accurate geometry of network and smooth coding of links, which are important since drivers' behavior in PARAMCIS is very sensitive to the network geometry;
(2) The signposting setting for links, which is used for defining locations of weaving area;
(3) Proportion of each type of vehicles;
(4) A lane-usage model, which was developed and plugged into PARAMICS simulation as a complementary module for improving the distribution of vehicles on each individual lane;
(5) Driver behavior factors in car-following and lane-changing models, including the mean target headway and mean driver's reaction time. The values of mean target headway and mean reaction time are set to 1.0 and 0.6, based on the calibration study by Gardes, et al. *(23)*;
(6) Definition of vehicle characteristics. We found better simulation results can be obtained when the acceleration and deceleration of cars are set to 2.8 m/s^2 and –5 m/s^2;

4.4 Calibration of ramp metering algorithms

4.4.1 Fixed-time control Plan

Vehicle-actuated fixed-time ramp control strategy is applied in the real world. For the ramps in our study area, metering plans are shown in Table 1. In this study, we use the same strategy and metering plan.

4.4.2 Design and Calibration of ALINEA Algorithm

The ALINEA algorithm has four parameters to be calibrated, including the location of the downstream detector station, the desired occupancy of the downstream detector station, the time interval to update the metering rate, and a constant regulator parameter K_R.

(1) The downstream detector should be placed at a location where the congestion caused by the excessive traffic flow originated from the ramp entrance can be detected. In reported implementations, this site was located between 40 m and 500 m downstream of the ramp.
(2) The desired occupancy can be equal to or around the occupancy at capacity, which can be found in the volume-occupancy relationship curve. Various values ranging from 0.18 to 0.31 have been found in previous applications.
(3) The regulator K_R, used for adjusting the constant disturbances of the feedback control, is found to yield good results in the real-life experiment when it is set to 70 veh / hour. Simulation results are considered to be insensitive for a wide range of values.
(4) The cycle for ramp metering implementation, or the time interval to update the metering rate, is also variable with the range from 40 seconds to 5 minutes.

The calibrated parameters used in this study are shown in Table 2. We accepted some empirical values derived from former studies. The definition of the desired occupancy is based on simulation results under the morning peek-hour scenario, which are used for drawing the volume-occupancy relationship curves of some mainline detector stations.

We found, for any a detector station in the study section, the threshold occupancy at capacity is generally in the neighborhood of 18 percent.

A queue override strategy is integrated to the ALINEA algorithm. A queue detector is located at the upstream end of the ramp for detecting excessive queue lengths. When the occupancy of the detector exceeds a certain threshold, metering rate is set to the maximum in order to avoid interference with surface traffic as soon as possible. In addition, a ramp volume restriction is also employed. The calculated metering rate should be limited within some pre-defined maximum and minimum values.

4.4.2 Calibration of BOTTLENECK Algorithm

The key point of the BOTTLENECK algorithm is to define the area of influence for each section. The area of influence of a section may include several ramps that are responsible for the volume reduction. We define a section as the freeway segment between two adjacent mainline detectors, and assume that on-ramps in the area of influence should be within a maximal distance of two miles from the location of downstream detector.

The stretch of freeway in the study area has thirteen sections and each section has an area of influence, shown in Figure 3. The share of volume reduction of a ramp is decided by the pre-defined weighting factors according to not only how far it is to the downstream detector station, but also the demand level of the ramp. Based on historical time-dependent OD demands derived from loop data, the weighting factors of each section in the study area are calculated, shown in Table 3.

The override strategy and ramp volume restriction used in the ALINEA algorithm are also applied in the BOTTLENECK algorithm.

4.4.3 Calibration of ZONE Algorithm

The ZONE algorithm needs to identify critical bottlenecks in the network first and then divides the entire network into multiple zones, whose downstream boundaries are located at the critical bottlenecks. Based on the analysis of real-world loop data, mainline detector stations at the post-mile of 2.35 and 4.03 are major bottlenecks in the network. The lane drop is the reason for the bottleneck at post-mile 2.35, and the high demands from on-ramp 4 and 5 cause the bottleneck at the post-mile of 4.03. Therefore, we define three zones for the study network, as illustrated in Figure 4. In each zone, each on-ramp has six pre-specified metering rates, calculated based on target demands, which are derived according to historical on-ramp flow during peek hours.

The metering rate look-up tables for each ramp in the study area are calculated and presented in Table 4. The metering rate here is cycle length. The green and yellow times of any cycle are 1.3 and 0.7 seconds, respectively. In addition, the occupancy thresholds for local-level occupancy control are defined based on Minnesota experiences *(8)*. The same definition of these thresholds was applied in the occupancy control strategy of the BOTTLENECK algorithm as well.

5. SIMULATION RESULTS AND DISCUSSION

Two scenarios were considered, morning peek-hour from 6:30 to 9:00 a.m. and afternoon peek hour from 3:30 to 6:00 p.m. Because demand patterns in the morning and in the afternoon are very different in the study area, we employ two sets of operational parameters for both BOTTLENECK and ZONE algorithms, shown in Table 4 and 5. Monte Carlo simulation is used to obtain the estimation of the system performance. Five simulation runs were conducted for a time period of two and one half hours under both morning peek-hour and afternoon peek-hour demands. The first ten minutes of each simulation run were treated as "warm-up" periods. For comparison purposes, we include simulation results corresponding to no ramp control.

The overall system performances are shown in Table 4. Figure 5 shows the variations of the average mainline travel time with respect to the time horizon under the morning scenario when using various ramp control strategies. These simulation results show that the two coordinated ramp-metering algorithms, i.e., BOTTLENECK and ZONE, are more efficient than the current fixed-time control under both morning scenario and afternoon scenario. The ZONE algorithm performs best among these three adaptive ramp-metering algorithms. ALINEA has a comparable performance with the fixed-time control under the morning scenario, but shows a better performance under the afternoon scenario.

The effects of various ramp control strategies on the metered ramps are shown in Table 6. Under different algorithms, the average waiting time (for the whole simulation period) on each ramp in the study area is visually shown in Figure 6. In order to further detail and better represent the performance of each algorithm, as an example, Figure 7 shows the travel time from ramp 3 to the downstream end of the freeway with respect to the time horizon under the morning scenario.

In the morning scenario, ramps 4 and 1 were identified by ZONE as major control points, while ramps 1, 3 and 4 were identified by BOTTLENECK and ramps 3, 1, 5 and 4 by ALINEA. ZONE has a comparatively good performance in decreasing the on-ramp waiting times of most ramps, except for ramp 4 under morning scenario. Compared to the ZONE algorithm, BOTTLENECK causes more delays to vehicles on entrance ramps and ALINEA causes the longest delay for those vehicles waiting to enter the freeway. Further analysis found that the major congestion of the study area derives from the large amount of traffic merging to I-405 from SR-133. There is no lane added after the merging of these two freeways. Therefore ramps 1 and 2, which are on the upstream freeway, are critical control points in the study area. In the morning, heavy traffic flow entered the freeway from ramps 3, 4 and 5. The free flow area is between the downstream of ramp 5 and the end of our study network. The last bottleneck before the free-flow area is the merging area of ramp 5, where a backward shockwave must be generated when large amount of traffic entering freeway from ramp 5. This shockwave conveyed backward and thus causes more serious congestion on the upstream of the freeway. The merging area of ramp 4 is just located at the area of the upstream of the shockwave. The ZONE algorithm selects ramp 4 as the major control point and thus achieves a good performance.

The advantages of the ZONE and BOTTLENECK algorithms are the coordination between ramps and the use of historical network demand pattern. BOTTLENECK and ZONE have distinctive features, but both of them can detect the traffic congestion inside the pre-defined section or zone. The feature of ZONE is that known bottlenecks identified during the pre-implementation phase and there are a large amount of works to be done for the design and calibration of the algorithm. The feature of BOTTLENECK is that it can dynamically identify a bottleneck in the network and thus can be used for real-time control since there is no need to calculate capacities off-line. The occupancy control strategy has been used for both BOTTLENECK and ZONE algorithms in the calculation of the local ramp-metering rate. ZONE algorithm considers the occupancy of the mainline detector stations up to three miles ahead of the ramp, while BOTTLENECK only takes the upstream detector station into consideration.

Though ALINEA is a local algorithm and has no ability of coordination, it can dynamically identify local travel demand pattern through the feedback control. This is an advantage compared with the studied two coordinated algorithms. Ramps 1 and 2, which are on the upstream freeway, are critical control points in the study area. For the morning scenario, the traffic flows on ramps 1 and 2 were light; the effect of ramp control was limited. For the afternoon scenario, there were enough traffic flows from ramps 1 and 2, which could generate a better effect of ramp control. This was the reason that ALINEA performed much better under the afternoon scenario.

6. CONCLUDING REMARKS

In this paper, a functionality-enhanced PARAMICS simulation laboratory for the evaluation of ramp metering algorithms is presented. The functionalities of PARAMICS has been enhanced by integrating complementary modules, including loop data aggregator, actuated signal controller, time-based ramp controller, etc., which are developed in PARAMICS API in order to better fit to the California traffic scenario and various ATMIS research. Based on the work conducted in this evaluation study, various other ATMIS applications can be tested and evaluated by this simulation laboratory.

We evaluated three ramp metering algorithms in this study, namely, ALINEA, BOTTLENECK, and ZONE. The simulation results show that the two coordinated ramp-metering algorithms, i.e. BOTTLENECK and ZONE, are more efficient than both the current fixed-time control and ALINEA under both morning scenario and afternoon scenario. The ZONE algorithm performs best among these three ramp-metering algorithms. When there are enough on-ramp volumes to be controlled by the ALINEA algorithm, ALINEA shows its potential to improve traffic congestion.

Though the two coordinated algorithms perform better in our study, they depend too much on the algorithm calibration based on historical data, i.e. the network demand pattern. If the network demand pattern is changed due to some unpredictable events or factors, these coordinated algorithms might not work well. Therefore, the dynamic identification and prediction of the network demand pattern should be incorporated into the future coordinated algorithms.

Since the urban road network was not included in our study, drivers' diversion behavior at the on-ramps was not modeled. For future studies, the integrated control that incorporates diversion, signal and ramp control should be modeled to study the impact of the route diversion on the performance of ramp metering.

ACKNOLEGEMENTS

This research was funded by the California Department of Transportation (Caltrans) through the California Partners for Advanced Transit and Highways (PATH) Program.

Scott Aitken and Ewan Speirs, from Quadstone in Scotland, provided invaluable technical support in the process of applying the Paramics model. Their continuous collaboration to the project greatly facilitated the work.

We wish to thank Xiaojian Nie and Taewan Kim of UC Davis for their valuable inputs to this paper.

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LIST OF TABLES

Table 1 Fixed-time metering plan used in the study area (Unit: seconds)

Time	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 6	Ramp 7
6-9 a.m.	6	12	5	7	5	6	7
3-7 p.m.	6	7	4	7	6	6	6

Table 2 Calibrated parameters of the ALINEA algorithm

Calibrated parameters	Calibrated values
Location of downstream detector station	60 m
Desired occupancy	0.18
Time interval of metering rate update	30 sec
Regulation parameter K_R	70 veh / hour
Ramp volume restriction (minimum and maximum)	200 veh / hour, 900 veh / hour
Occupancy threshold of the queue detector	50%

Table 3 Weighting factors calibrated for the BOTTLENECK algorithm

Ramp #		Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sec. 5	Sec. 6	Sec. 7	Sec. 8	Sec. 9	Sec. 10	Sec. 11	Sec. 12	Sec. 13
AM	1	0	1	0.7	0.7	0.7	0.2	0	0	0	0	0	0	0
	2	0	0	0.3	0.3	0.3	0.1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0.7	1	1	0.6	0.34	0	0	0
	4	0	0	0	0	0	0	0	0	0.4	0.17	0.26	0.33	0
	5	0	0	0	0	0	0	0	0	0	0.49	0.74	0.18	0
	6	0	0	0	0	0	0	0	0	0	0	0	0.49	0.37
	7	0	0	0	0	0	0	0	0	0	0	0	0	0.63
PM	1	0	1	0.48	0.48	0.48	0.2	0	0	0	0	0	0	0
	2	0	0	0.52	0.52	0.52	0.1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0.7	1	1	0.8	0.35	0	0	0
	4	0	0	0	0	0	0	0	0	0.2	0.1	0.2	0.43	0
	5	0	0	0	0	0	0	0	0	0	0.55	0.8	0.11	0
	6	0	0	0	0	0	0	0	0	0	0	0	0.46	0.43
	7	0	0	0	0	0	0	0	0	0	0	0	0	0.57

Table 4 Metering rate look-up table for each ramp in the ZONE algorithm

	Occupancy threshold	Rate level	Zone 1			Zone 2				Zone 3		
			5-min Vol. threshold	ramp 1	ramp 2	5-min Vol. threshold	ramp 3	ramp 4	ramp 5	5-min Vol. threshold	ramp 6	ramp 7
AM	< 0.15	1	> 91	3.3	18	> 224	3.8	6.9	2.6	> 214	3.5	2.1
	< 0.17	2	> 84	3.8	20	> 192	4.4	8.0	3.0	> 184	4.0	2.4
	< 0.18	3	> 70	4.5	23	> 160	5.1	9.4	3.5	> 153	4.8	2.8
	< 0.23	4	> 56	5.6	27	> 128	6.3	11.4	4.3	> 122	5.8	3.5
	< 0.40	5	> 42	7.1	33	> 96	8.1	14.8	5.5	> 92	7.5	4.5
	> 0.40	6	< 42	10	43	< 96	11.3	20.7	7.7	< 92	10.5	6.3
PM	< 0.15	1	> 217	2.7	2.5	> 157	2.6	6.4	9.6	> 91	6.6	5.0
	< 0.17	2	> 186	3.1	2.9	> 134	3.0	7.4	11.1	> 84	7.7	5.8
	< 0.18	3	> 155	3.7	3.4	> 112	3.5	8.7	13.1	> 70	9.1	6.8
	< 0.23	4	> 124	4.5	4.1	> 90	4.3	10.7	16.0	> 56	11.1	8.3
	< 0.40	5	> 93	5.8	5.3	> 67	5.5	13.7	20.6	> 42	14.2	10.7
	> 0.40	6	< 93	8.1	7.4	< 67	7.7	19.2	28.8	< 42	19.9	15.0

Table 5 Overall performances under various ramp control strategies

		GTVTT (sec) and time saving	AMTT (sec) and time saving
AM	No control	17718790.0	786.8
	Fixed-time	15357714.0 (-13.3%)	662.7 (-15.8%)
	ALINEA	15346377.0 (-13.4%)	668.3 (-15.1%)
	BOTTLENECK	14881531.0 (-16.0%)	644.5 (-18.1%)
	ZONE	14447638.0 (-18.5%)	628.6 (-20.1%)
PM	No control	13356859.0	585.3
	Fixed-time	13439063.0 (+0.6%)	574.2 (-1.9%)
	ALINEA	13184707.0 (-1.3%)	535.0 (-8.6%)
	BOTTLENECK	12290489.0 (-8.0%)	513.4 (-12.3%)
	ZONE	12080640.0 (-9.6%)	508.4 (-13.1%)

Table 6 Performance measures of on-ramps under various ramp control strategies

RAMP #		AM		PM	
		AOWT for the whole simulation period (sec)	AODTT for the whole simulation period(sec) and time saving	AOWT for the whole simulation period (sec)	AODTT for the whole simulation period(sec) and time saving
1	No control	0.06	618.1	0.12	571.0
	Fixed-time	2.0	593.5 (-4.0%)	3.2	569.3 (-0.4%)
	Alinea	29.6	676.4 (+9.4%)	15.3	572.5 (+0.3%)
	Bottleneck	26.9	626.4 (+1.3%)	18.1	556.6 (-2.5%)
	Zone	8.7	577.1 (-6.6%)	5.5	541.6 (-5.1%)
2	No control	0	573.5	0.56	530.8
	Fixed-time	3.0	546.4 (-4.7%)	27.7	575.1 (+8.3%)
	Alinea	3.6	598.4 (+4.3%)	28.0	556.0 (+4.7%)
	Bottleneck	5.1	539.6 (-6.0%)	40.6	567.5 (+6.9%)
	Zone	4.9	529.0 (-7.8%)	9.2	518.9 (-2.2%)
3	No control	0.11	291.1	0.2	288.7
	Fixed-time	1.5	300.0 (+3.1%)	1.5	294.6 (+2.0%)
	Alinea	33.2	348.4 (+19.7%)	47.7	372.6 (+29.1%)
	Bottleneck	14.7	317.1 (+8.9%)	20.2	325.8 (+12.9%)
	Zone	5.1	299.8 (+3.0%)	2.2	294.2 (+1.9%)
4	No control	0	254.8	0	243.7
	Fixed-time	3.4	262.7 (+3.1%)	0.2	250.4 (+2.7%)
	Alinea	9.3	268.7 (+5.5%)	1.3	247.8 (+1.7%)
	Bottleneck	9.3	268.3 (+5.4%)	1.1	248.1 (+1.8%)
	Zone	36.7	297.4 (+16.7%)	1.4	250.4 (+2.7%)
5	No control	0.25	224.9	0.03	218.7
	Fixed-time	1.6	229.7 (+2.1%)	1.3	223.8 (+2.3%)
	Alinea	16.8	256.1 (+13.9%)	3.8	226.8 (+3.7%)
	Bottleneck	5.6	238.2 (+5.8%)	1.1	223.4 (+2.1%)
	Zone	1.9	229.9 (+2.2%)	3.5	227.2 (+3.9%)
6	No control	0.2	147.7	0	145.1
	Fixed-time	2.0	152.6 (+3.3%)	1.9	148.7 (+2.5%)
	Alinea	1.9	151.2 (+2.4%)	1.2	147.9 (+1.9%)
	Bottleneck	1.6	150.2 (+1.7%)	1.2	147.8 (+2.5%)
	Zone	1.1	150.4 (+1.8%)	1.4	149.3 (+2.9%)
7	No control	0.2	122.6	0.3	119.4
	Fixed-time	2.4	129.7 (+5.8%)	1.7	126.0 (+5.5%)
	Alinea	1.7	129.8 (+5.9%)	1.3	124.5 (+4.3%)
	Bottleneck	1.4	129.2 (+5.4%)	1.1	124.6 (+4.4%)
	Zone	1.2	123.4 (+0.7%)	1.7	124.9 (+4.6%)

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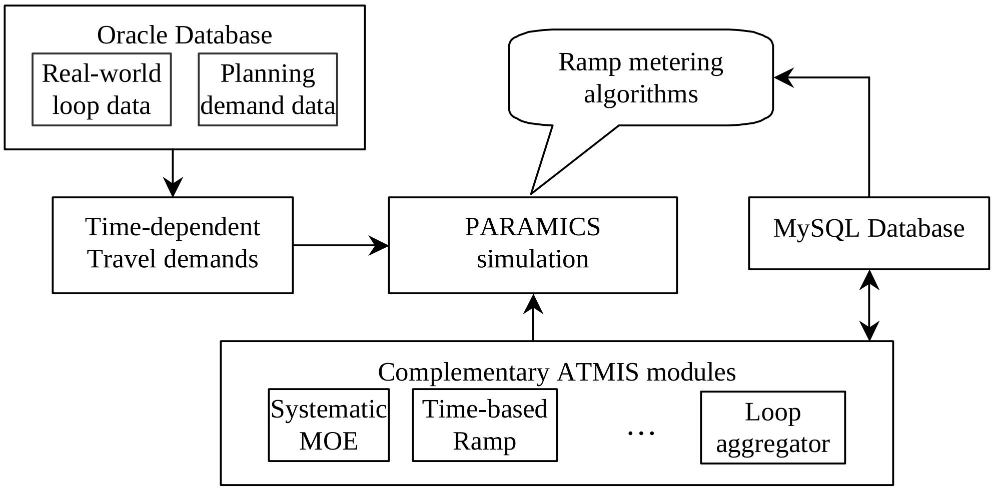


Figure 1 Framework of simulation laboratory the evaluation study

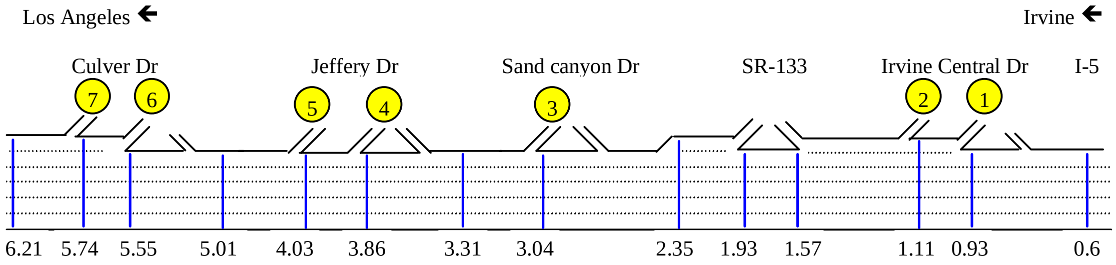


Figure 2 Schematic of freeway lanes, detector locations, on-ramps and off-ramps

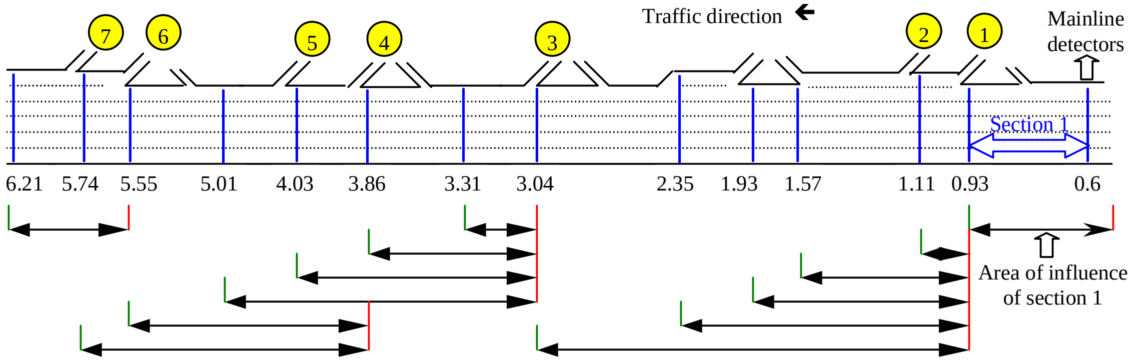


Figure 3 Definition of an area of influence for each section in the Bottleneck algorithm

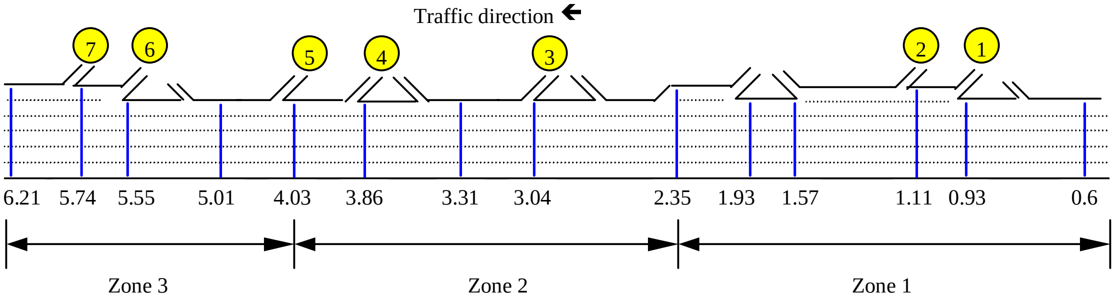


Figure 4 Definition of zones in the Zone algorithm

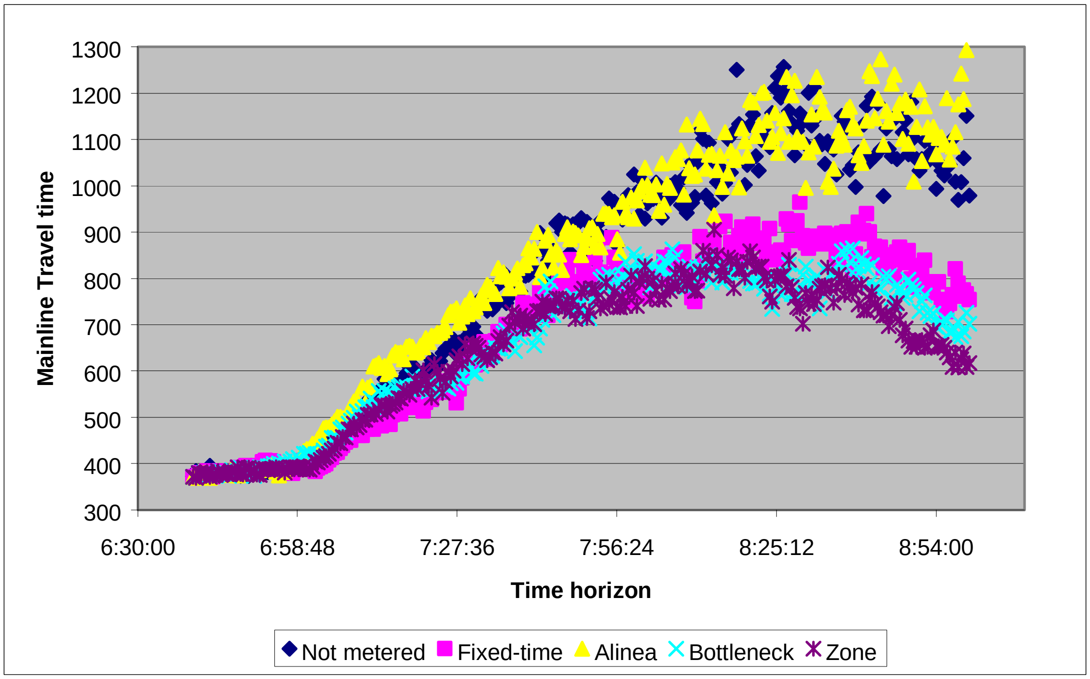
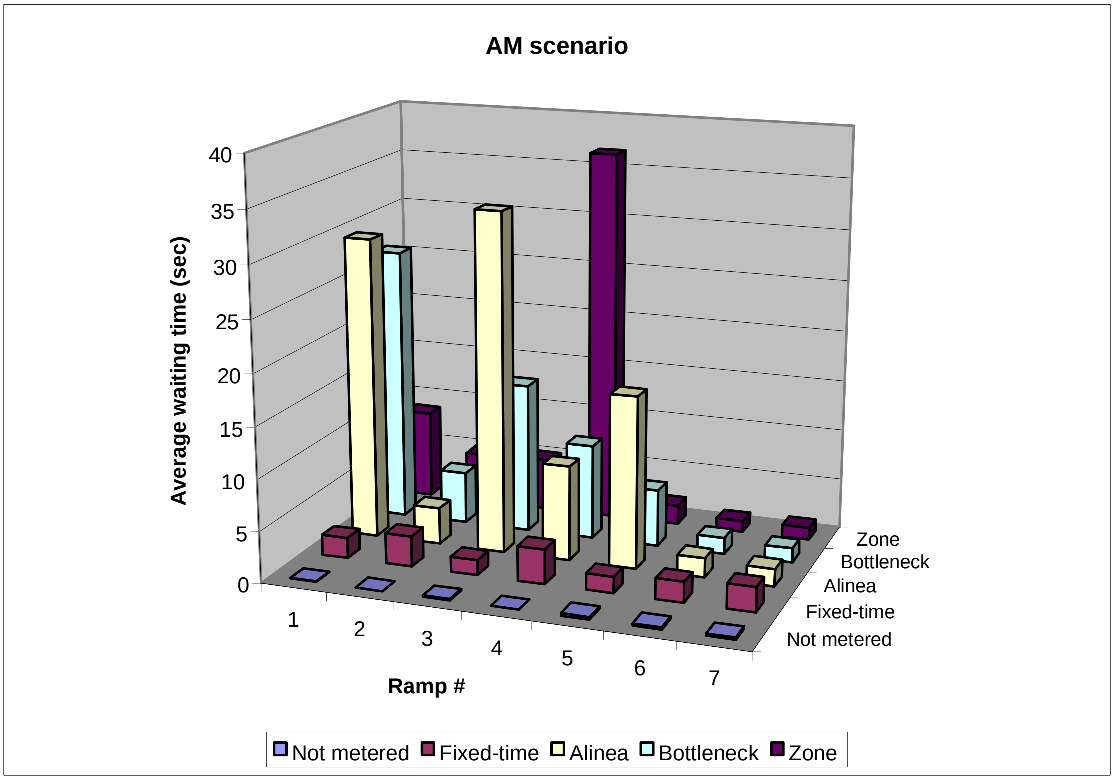


Figure 5 Comparison of the variation of mainline travel time when using different ramp control strategies under morning scenario (based on one simulation run)



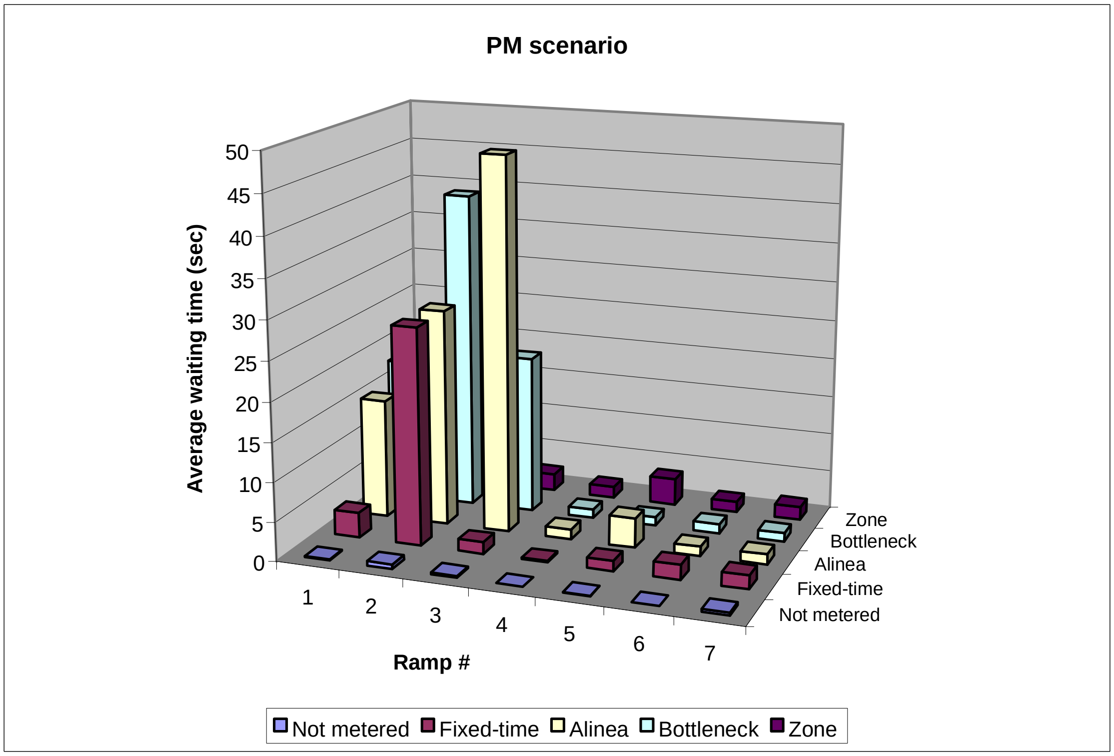


Figure 6 Average waiting time on entrance ramps when using various ramp control strategies

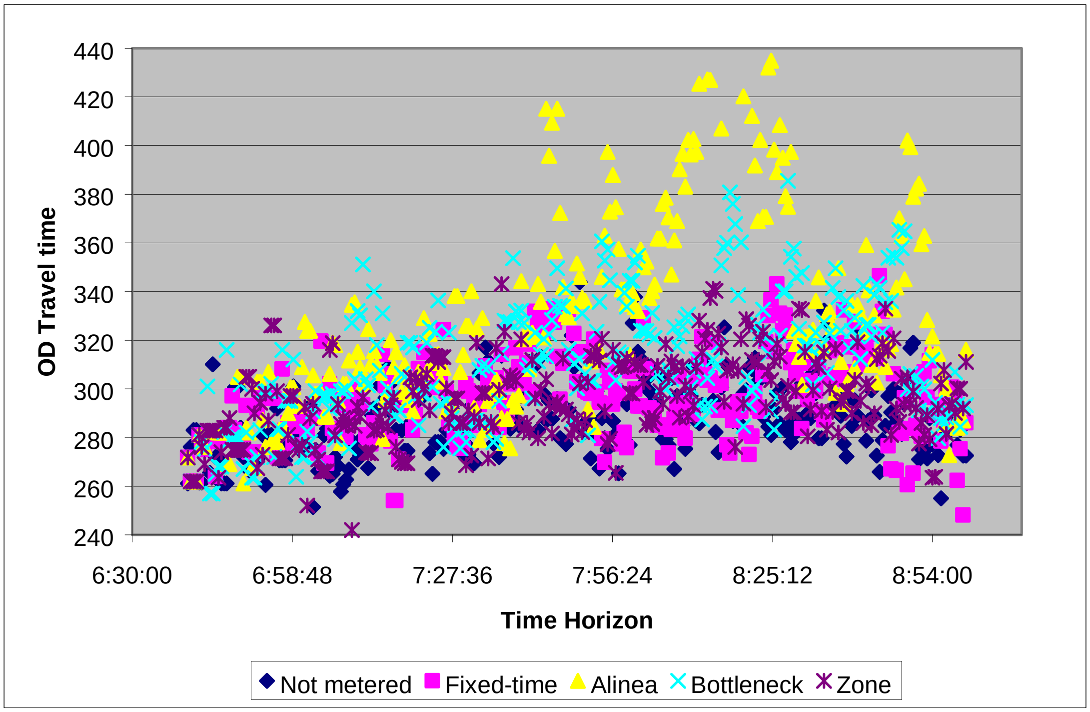


Figure 7 Comparison of the variation of OD travel time when using different ramp control strategies under morning scenario (based on one simulation run)