2005-48

Final Report

Evaluation and Improvement of the Stratified Ramp Metering Algorithm Through Microscopic Simulation - Phase II

MINNESOTA DEPARTMENT OF TRANSPORTATION

Research

Technical Report Documentation Page

1. Report No. MN/RC – 2005-48	2.	3. Recipients Accession No.
4. Title and Subtitle Evaluation and Improvement of the Stratified Ramp Metering Algorithm Through Microscopic Simulation - Phase II		5. Report Date December 2005
		6.
7. Author(s) Panos Michalopoulos, John Hourdos, Wuping Xin		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering University Of Minnesota 500 Pillsbury Dr S E Minneapolis, MN 55455		10. Project/Task/Work Unit No.
		11. Contract (C) or Grant (G) No. (c) 81655 (wo) 96
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/pdf/200548.pdf		

16. Abstract (Limit: 200 words)

A new ramp metering strategy implemented on the Twin Cities freeway system to reduce ramp waiting times was evaluated through microsimulation of freeway activity. The study compared Stratified Ramp Metering strategy with the previous Zone Metering Strategy and with no control strategy.

Comparison with Zone, which was designed to favor freeway flow, showed the new strategy succeeded in greatly reducing ramp delays and lines. When compared to the results of no control strategy, it reduces freeway travel time, increases freeway speed, smoothes the flow of traffic, and reduces the number of stops.

However, travel time, fuel consumption and pollutant emissions are unpredictable under the newer system. Compared to no control strategy, such measures of effectiveness may improve or worsen depending on the freeway patterns and demand.

Based on these findings, the researchers will seek improvements to the design of the Stratified Ramp Metering algorithm so as to factor in disruptive traffic patterns.

17. Document Analysis/Descriptors Ramp metering Microsimulation Traffic flow	Travel time Speed	18.Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 110	22. Price

Evaluation and Improvement of the Stratified Ramp Metering Algorithm Through Microscopic Simulation - Phase II

Final Report

Prepared by:
Panos Michalopoulos
John Hourdos
Wuping Xin

Department of Civil Engineering
University Of Minnesota

December 2005

Published by:
Minnesota Department of Transportation
395 John Ireland Boulevard
St. Paul, MN 55155

Table of Contents

List of Figures

List of Tables

Executive Summary

As a result of the recent controversy regarding ramp metering effectiveness, the new Stratified Ramp Metering strategy was just deployed in the Twin Cites freeway system. This recently deployed ramp control strategy termed “Stratified Metering Strategy” is extensively evaluated through rigorous micro-simulation of actual freeway deployments and compared with the earlier ZONE Metering Strategy as well as the No Control alternatives.

The evaluation results are consistent with qualitative observations, and confirm that the new ramp control strategy meets its objective in substantially reducing ramp delays and queues caused by the over-restrictive metering rates of the ZONE algorithm. The results also indicate that when compared to the No Control alternative, Stratified Ramp Control is effective in reducing freeway travel time and delay, increasing freeway speed, smoothing freeway flow as well as reducing the number of stops. However, system delay, travel time as well as fuel consumption and pollutant emissions under the Stratified control are unpredictable, i.e., these measures of effectiveness may improve or degrade as compared to No Control alternative, depending on the freeway geometry and demand patterns. As expected, the new strategy cannot be as effective as the ZONE strategy on a system wide basis due to the constraints imposed on the ramp delays.

In addition, a sensitivity analysis was carried out in order to understand the inner workings of the Stratified Ramp Metering algorithm and facilitate the finding of optimal operational parameters through fine-tuning. Based on the findings from the research, improvements to the design of the Stratified Ramp Metering algorithm will be explored so as to better factor in ramp queues and other traffic pattern measurements such as the formation of shockwaves.

Chapter 1: Introduction

Freeways by design are expected to be free-flowing and provide the desired level of service. In recent years, however, it is not uncommon for freeway traffic to become highly congested, even reach a stop-and-go state during peak periods (Chardhary et al., 2000). Of the various measures intended to alleviate freeway congestion, ramp control has been increasingly recognized as one of the most effective and viable strategies since its first deployment in the 1960s. In effect, the function of ramp control is (1) to limit the entering traffic from exceeding the operational freeway capacity and (2) to provide more efficient and smoother merging at the freeway entrance by breaking up vehicle platoons. The benefits of ramp control reported in the literature include improved use of freeway capacity, increased throughput and freeway average speed, alleviated congestion, reduced system travel time as well as environmental benefits (Arnold, 1998; Cambridge Systematics, 2001; Elefteriadou, 1997; Papageorgiou et al., 1997; Taylor et al., 1996; Zhang and Levinson, 2003).

In the Twin Cities metropolitan area, freeway ramp metering goes back as early as 1969, when the Minnesota Department of Transportation (Mn/DOT) first tested ramp metering in a I-35E pilot project. To date, the Twin Cities ramp metering system has grown to include 419 ramp meters, with 213 operating during the morning and 266 in the afternoon. Prior to year 2000, the deployed control strategy, i.e., the ZONE Metering strategy (Lau, 1996), focused on maximizing freeway capacity utilization without handling ramp queue spillbacks and controlling ramp waiting times. With this strategy, breakdowns at freeway bottlenecks can be effectively prevented; yet ramp delays and queues were often excessive. (Cambridge Systematics, 2001; Hourdakis and Michalopoulos, 2002). The latter resulted in public concerns, leading to a six-week system-wide shutdown study in late 2000.

The study confirmed the overall benefits of the ZONE strategy; however, it also “highlighted the need for modifications towards an efficient but more equitable ramp control algorithm” (Cambridge Systematics, 2001). In response, Mn/DOT developed a new one aiming to strike a balance between freeway efficiency and reduced ramp delays. This new strategy, termed Stratified Zone Metering (SZM), takes into accounts not only freeway conditions but also real time ramp demand and queue size information (Xin et al.,2004). Implementation of the new strategy with the Twin Cities freeway system began in early 2002; full deployment was completed in 2003.

The purpose of this report is to present a detailed description of the Minnesota Stratified Zone Metering (SZM) strategy and present the results from evaluating its effectiveness on actual freeway deployments through micro-simulation. In order to arrive at comprehensive conclusions, the study not only compares the new strategy to the pre-shutdown ZONE strategy, but also to the No Control alternative through rigorous micro-simulation cap taking into account a wide range of demand patterns and differing freeway geometries. Simulation is the only practical way of achieving the evaluation objectives not only due to time and cost constraints but also because the experiment can be kept under controlled conditions for meaningful comparisons of different ramp control strategies. Finally, the evaluation results indicate that the Stratified Zone Metering Strategy meets its objective of controlling ramp queue spillbacks and reducing ramp delay; also it is still beneficial as compared to the No Control alternative in terms of improving freeway performance and safety. However, this is accomplished at the expense of freeway and system performance as expected.

Chapter 2: Background

There is a large body of theoretical research in the literature that deals with ramp control problems. One of the first attempts in this direction involved application of optimization techniques maximizing a certain freeway or system performance index subject to the physical constraints of the freeway system (Chen et al., 1974; Wang and May, 1973; Wattleworth and Berry 1965; Yuan and Kreer 1971; Zhang and Levinson, 2003). Following this, optimal control theory and macroscopic flow models were combined to achieve optimal coordinated ramp control (Isaksen and Payne, 1973; Papageoriou, 1983; Papageoriou et al., 1990; Papageoriou et al., 1991; Zhang et al., 1994; Stephanedes and Chang, 1993; Zhang et al. 1996; Chang et al. 2002). Some of these developments have been successfully implemented in real life (Papageoriou et al., 1997), while others, due to computational complexity and increasing inaccuracies involved in the OD estimation process, have limited practical feasibility.

On the other hand, over the years numerous empirical ramp control strategies have been developed and deployed in the field. Some noteworthy examples of field deployed integrated ramp control include the ZONE in Twin Cities, Minnesota; Bottleneck algorithm in Seattle, Washington; Helper algorithm in Denver, Colorado; Swarm in Orange County, California; Metaline in Paris and Amsterdam. In addition to these, there are a number of proposed ramp metering algorithms awaiting further assessment and future implementation (Bogenberger and May, 1999).

Minnesota Ramp Control Algorithms

When implementing a ramp control strategy, a transportation agency can either give priority to the freeway in order to prevent mainline congestion (i.e., freeway first policy), or balance the previous objective with the need to avoid excessive ramp delays, queues, or spillbacks to local streets (i.e., balanced policy). In short, the pre-shutdown ZONE algorithm adopted the "freeway first" principle, while its successor, Stratified Zone Metering Strategy strives to achieve balanced conditions for the entire system (freeway and ramps).

ZONE Metering Strategy

The ZONE Metering Strategy begins by dividing the freeway into zones. A zone is a unidirectional freeway section, identified by an upstream free-flow area and a downstream bottleneck location. The

ZONE metering algorithm is built on the basic philosophy of balancing the volumes entering and leaving the zone. It is implicitly assumed that when the total volumes entering and departing are balanced, variations of zone density are maintained within a narrow range; thereby flow is smoothed out and the level of service is improved as compared to the No Control alternative. This philosophy is expressed in the zone conservation equation:

$$M+F = X+B+S-(A+U) \tag{1}$$

Where

M represents the total local-access ramp volume to be controlled;

F represents the total freeway-to-freeway ramp volume to be controlled;

A represents the measured upstream mainline volume;

U represents the total measured non-metered ramp volume;

X represents the total exit ramp volumes;

B represents the downstream bottleneck capacity;

S represents the spare capacity i.e., the space available within the zone when the zone density is low.

Each individual variable in equation (1) has a target value (denoted by *t*). The zone conservation equation written in the target form is expressed as $\mathrm{M}_t+F_t=X_t+B_t+S_t-A_t-U_t$. The target values in this equation are derived from historical data in the past 15 days except S_t , which is set to zero, indicating no space available in target condition. The selection of applicable metering rates is based on a comparison of the real-time $M+F$ to a series of thresholds in the format of $\lambda_1 M_t + \lambda_2 F_t$, where λ_1 and λ_2 are the empirically-predetermined multiplying factors. The resultant metering rates are referred to as volume-based metering rates, as they are determined from traffic volumes only.

In case of freeway incidents, volume-based metering rates may become invalid, since a temporary bottleneck would be created, requiring more restrictive rates to prevent further breakdown. To allow for this, the ZONE metering algorithm utilizes an occupancy-feedback mechanism (referred to as occupancy control) to apply local adjustments. In this mechanism, each metered ramp is associated with certain number of freeway downstream detector stations, from which the highest occupancy measurement determines an occupancy-based metering rate. Of the occupancy-based rate and the volume-based rate, the more restrictive one will be implemented in the field.

Stratified Zone Metering Strategy

The Minnesota Department of Transportation (Mn/DOT) operates nearly 430 ramp meters to control access on approximately 210 miles of freeway in the Twin Cities Metropolitan area. An integrated system wide traffic responsive ramp control strategy, ZONE metering had been successful for the last few decades in alleviating congestion on the Twin cities' freeways. However, excessive ramp delays due to freeway demand surge on specific ramps mandated an 8-week ramp meter shutdown study (Cambridge Systematics, 2001). The study confirmed the overall system wide benefits of ramp metering. Nevertheless, the findings also showed that, as the objective of Zone metering strategy focuses only on maximizing freeway throughput, ramp queues remain unchecked thereby resulting in unacceptable ramp delays and spillbacks.

Following the shutdown study, MnDOT modified the control objective to implement a queue control policy and devised the new Stratified Zone Metering algorithm (henceforward referred to as SZM). The objective of the new strategy is still to maximize freeway throughput but with an additional constraint to limit the waiting time on the ramps to a predetermined maximum. The implementation of SZM in the Twin Cities metro area started in March 2002 and it has been only recently that its full deployment was accomplished.

To help identify all the parameters and their importance in the Stratified ramp control, a concise description of the algorithm is presented here. Interested readers can find a detailed description along with an illustrative example of design of the algorithm in Xin et al., 2004 and Lau, 2001. In this report all the parameters of the SZM control strategy are represented in bold typeface.

Data Processing

The functionality of SZM control strategy is entirely dependent on real time 30 second occupancy and volume data from the loop detectors in the metro area. Unlike occupancy, volume counts are discrete and when converted to hourly rates these discontinuities blow up resulting in a flow rate function with noise. Hence, all hourly flow rates need to be smoothed by a floating average to capture overall trends. Smoothing in SZM algorithm is done according to the following equation

$$F_t = F_{t-1} + K * (G_t - F_{t-1}) \tag{1}$$

where, t = 1,2,3…is the sampling index;

F_t and F_{t-1} are the smoothed flow rates for the current and previous sampling intervals respectively;

G_t is the current unsmoothed hourly flow rate; and

K is a smoothing constant that indicates degree of smoothing.

Ramp Demand processing

Ramp demand processing is the first step in the control logic. On each ramp, typically two types of detectors are deployed to measure the ramp demand in real time; a queue detector at the upstream end of the ramp and a passage detector immediately downstream to the ramp meter.

Ramp demand is the smoothed hourly flow rate calculated from the 30 second volume counts typically from a queue detector. In case of malfunctioning or absence of a queue detector, passage detector volume counts are used. However, as a passage detector cannot measure the true entrance demand, its 30 second volume is increased by a factor to prevent excessive queuing. This factor is called the Passage Correction factor *(**P_c**)*.

$$D_t = D_{t-1} + K_P * (P_c * V_t - F_{t-1}) \tag{2}$$

where

K_P is the ramp demand smoothing factor

When the ramp queue extends beyond its queue detector, the queue detector no longer gives an accurate measurement of the ramp demand. Such a condition is identified from the high occupancy measurements at the queue detector. Hence, whenever queue detector occupancy exceeds an empirically determined threshold *(**$O_{threshold}$**: 25%)*, a 30-second step increment in ramp demand *(**I_{ramp}**: 150 veh/hr)* is added to the smoothed flow rate.

Ramp queue Control

Estimation of ramp queue is of prime importance to the SZM control strategy as the strategy aims to restrict the maximum waiting time on a ramp. The queue size is calculated as the product of queue storage length *(L)* and queue density *(Q_d)*.

$$N = Q_d * L \tag{3}$$

where

L is the queue storage length in feet between the ramp meter and the queue detector

Q_d is the queue density estimated using a smoothed metering release rate called the accumulated release rate (R_a).

$$Q_d = 206.715 - 0.03445 * R_a \tag{4}$$

The queue density estimation based on the above equation is empirical but proved statistically significant throughout the control period. However, efforts for further improvement in the accuracy of the queue estimation are underway. Within the scope of the present study, the sensitivity of this equation is indirectly tested by considering the slope *(Q_{slope}: -0.03445)* and intercept *($Q_{Intercept}$: 206.715)* of the queue estimation equation as parameters of the algorithm.

To keep the ramp wait times below a predetermined Maximum Waiting Time Threshold (***T_{max}***), for each metered ramp a Minimum Release Rate *(r_{min})* is calculated based on the estimated queue size. Thus, to ensure that the last vehicle in the queue will not wait more than ***T_{max}***, the ramp's minimum release rate for that control interval should be,

$$r_{\min} = \frac{N}{T_{\max}} \tag{5}$$

where N is the queue size estimated from Eq.(3)

Minimum release rate determined as above should be in between an Absolute maximum Release rate *(**R_{max}** : 1714 veh/hr)* and Absolute Minimum Release rate *(**R_{min}** : 240 veh/hr)*. Metering rate is adjusted accordingly if not within this range.

Zone Flow Balance

Zone Flow Balance is the central element of Stratified Zone Metering control. A *zone* is defined as a continuous stretch of freeway with mainline detector stations as end points. It is identified as a group of consecutive mainline stations with number of stations in a zone varying from two to seven. Thus, the entire freeway segment is divided into groups of zones containing 2, 3…7 consecutive stations. Each such Zone group constitutes a Layer. As there are zones of six different sizes, six layers can be identified one for each zone size (see figure 2.1). In other words, all mainline stations on the entire freeway are grouped in sets of two, three, and so on up to seven, and all consecutive zones with same number of stations are said to form a layer. Therefore, every mainline station (with an exception for those near the boundaries) gets associated with six zones upstream and six zones downstream to it. As it can be readily seen, Zones overlap with zones of other sizes (see figure 2.3). The concept behind choosing seven as the maximum number of stations in a zone to be seven is that it is believed that to alleviate a bottleneck, controlling meters within a distance of 3 miles (stations are approximately half a mile apart) is sufficient for the next control interval of 30 seconds.

A layer is defined as a continuous stretch of all successive zones of the same size. As there are zones of six different sizes, six layers can be identified one for each zone size (refer fig 2.3). As it can be readily seen, zones overlap extensively, within and across layers. This Zone-Layer structure enables SZM to achieve a system wide control. Moreover, unlike its predecessor, identification of potential bottlenecks is not required in the SZM control due to an extensive overlap of zones.

Once the zone-layer structure is built, the next step is to process what is known as a metering rule. A metering rule is a zone inequality which reflects the basic control objective of SZM; to maintain the number of vehicles entering a zone less than that leaving the zone. In terms of the possible inputs and output flows within a given zone, the zone inequality takes the form as:

$$M + A + U \leq B + X + S$$

i.e.,

$$M \leq B + X + S - A - U \qquad (6)$$

where,

M is the total metered entrance ramp flow (controlled by the Algorithm)

A is the measured upstream mainline flow

U is the total measured unmetered entrance ramp flow

X is the total measured exit ramp flow

B is the downstream mainline capacity

S is the spare capacity on the mainline

Upstream mainline flow A, unmetered entrance ramp U and exit ramp flow X are smoothed based on Eq. (1) using their corresponding smoothing constants $\boldsymbol{K_M}$, $\boldsymbol{K_U}$ and $\boldsymbol{K_X}$ respectively. Just as the ramp demand smoothing constant $\boldsymbol{K_D}$, the constants $\boldsymbol{K_M}$, $\boldsymbol{K_U}$ and $\boldsymbol{K_X}$ smoothing constants are also the parameters of the algorithm and are included in the present study.

The downstream mainline capacity *(B)* is the expected mainline capacity at that location. It is calculated based on the capacity estimate of rightmost lane *($\boldsymbol{C_R}$)* and the capacity estimate for other lanes *($\boldsymbol{C_O}$)*. Specifically,

$$DownstreamMainlineCapacity(B) = C_R + (NumberOfLanes - 1) * C_O \qquad (7)$$

where, capacity estimates $\boldsymbol{C_R}$ and $\boldsymbol{C_O}$ are the parameters of the algorithm

The term Spare capacity *(S)* is introduced to measure the unoccupied capacity in the zone so that the ramp meters that are affected by the zone's rule, can be less restrictive than otherwise. More specifically, spare capacity is calculated as,

$$S = (FullDensity - ZoneDensty) * LaneMiles \qquad (8)$$

where, *FullDensity* ($\boldsymbol{D_f}$*: 32 veh/mile)*, a parameter of the algorithm, is a predefined threshold of density, above which the mainline is regarded to have no spare capacity left. It should be noted that this threshold is not meant to be an indicator of the onset of congestion.

The process of distributing a zone's maximum allowed metered input *(M)* among its metered ramps is known as zone's rule processing. Under Stratified Zone Metering, zones are processed sequentially based on layers; starting from the first zone in the first layer to the last zone in the sixth layer. For each zone in this sequence, the rule processing is done as follows:

i) Calculate the total allowed metered entrance ramp input *(M)* into the zone using Eq. (6)

ii) Calculate the sum of the demands from all the metered ramps within the zone

$$\sum_i D = D_1 + D_2 + D_3 + \ldots + D_n \qquad (9)$$

where n is the number of metered ramps within the zone

iii) Propose a weighted release rate (R_i^p) for each metered ramp, in proportion to the individual ramp demand (D_i)

$$R_i^p = M * \left[\frac{D_i}{\sum_i D_i} \right] \quad \forall\ i = 1, 2, 3 \ldots n \qquad (10)$$

iv) All metered ramps in the zone, at this moment, should have *minimum release rate* (r_{min} *from Eq.5),* a *release rate* proposed from a previous rule processing and the new *proposed release rate (* R_i^p from *Eq.10).* The initial value of the *release rate* is set to the *Maximum release rate* ($\boldsymbol{R_{max}}$ *: 1714 veh/hr)* and may get modified as the zones are processed. The *proposed release rate* R_i^p is compared with the *minimum release rate* and *release rate* for each ramp meter and such a comparison results in zone balance. If the *proposed rate* is less than the *minimum release rate*, the zone balance is reduced by the difference while if the *proposed rate* is greater than the *release rate*, the zone balance is increased by the difference

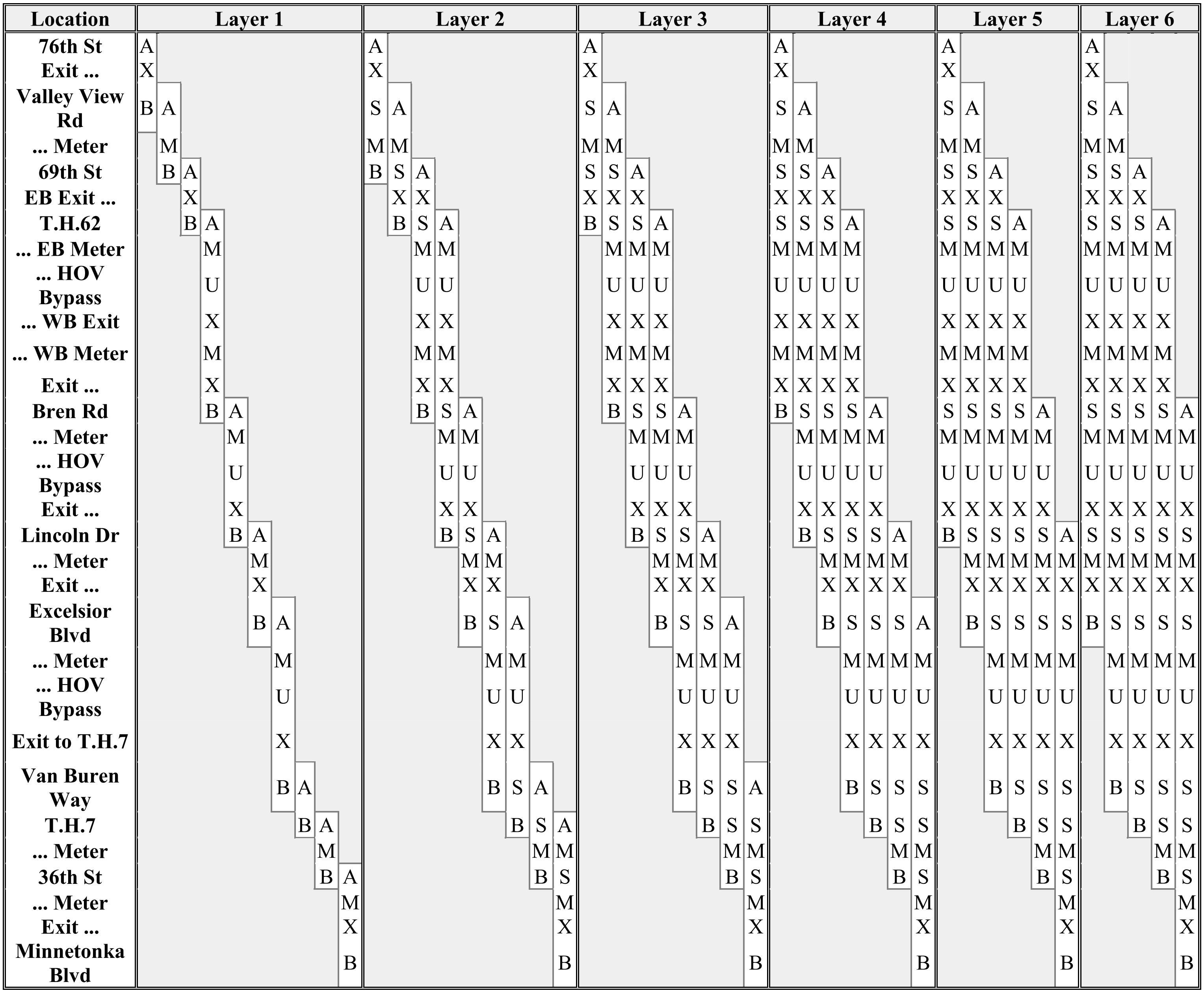
v) If the zone balance is below zero, each meter that reduced the zone balance gets it finalized release rate as the minimum release rate. Otherwise, the release rates of all the meters that increased the balance remain unchanged. Then the zone is processed again excluding the finalized meters and deducting their respective release rates from the total allowed metered input *(M)*. This iterative process continues until a zero zone balance is achieved.

This rule processing is done sequentially for all zones in all layers and this finalizes the release rates of all metered ramps as *field rates* for the next 30-second control interval.

All the control parameters of the SZM control are tabulated along with their current practice default values in Table 2.1.

No:	SZM Control Parameter	Notation	Units	Current Value
1	Absolute Maximum Release Rate	R_{max}	Veh/hr	1714
2	Absolute Minimum Release Rate	R_{min}	Veh/hr	240
3	Increment to ramp demand	I_{ramp}	Veh/hr	150
4	Full Density of a zone	D_f	Veh/mile	32
5	Max. Allowed waiting time on Local ramps	$T_{max, L}$	Seconds	240
6	Max. Allowed waiting time on F-F ramps	$T_{max,F}$	Seconds	120
7	Queue Density equation-Intercept	$Q_{Intrecept}$	Veh/mile	206.715
8	Queue Density equation-Slope	Q_{Slope}	Hr/mile	0.03445
9	Capacity Estimate for Rightmost mainline lane	C_R	Veh/hr	1800
10	Capacity Estimate for Other mainline lanes	C_O	Veh/hr	2100
11	Occupancy Threshold	O_{Th}	%	25
12	Ramp Meter Turn off threshold	M_{off}	%	80
13	Ramp Meter Turn on threshold	M_{on}	%	85
14	Passage Compensate Factor	P_c	-	1.15
15	Accumulate Release rate smoothing factor	K_R	-	0.20
16	Queue Detector smoothing factor	K_D	-	0.15
17	Passage Detector smoothing factor	K_P	-	0.20
18	Mainline station smoothing factor	K_M	-	0.15
19	Unmetered station smoothing factor	K_U	-	0.15
20	Exit station smoothing factor	K_X	-	0.15

Table 2.1 Control Parameters of Stratified Zone Metering



A- Upstream station, X- Exit ramp, B- Downstream station, M- Metered ramp, U- Unmetered ramp

Figure 2.1 Stratified Zone Metering Example (TH 169 NB)

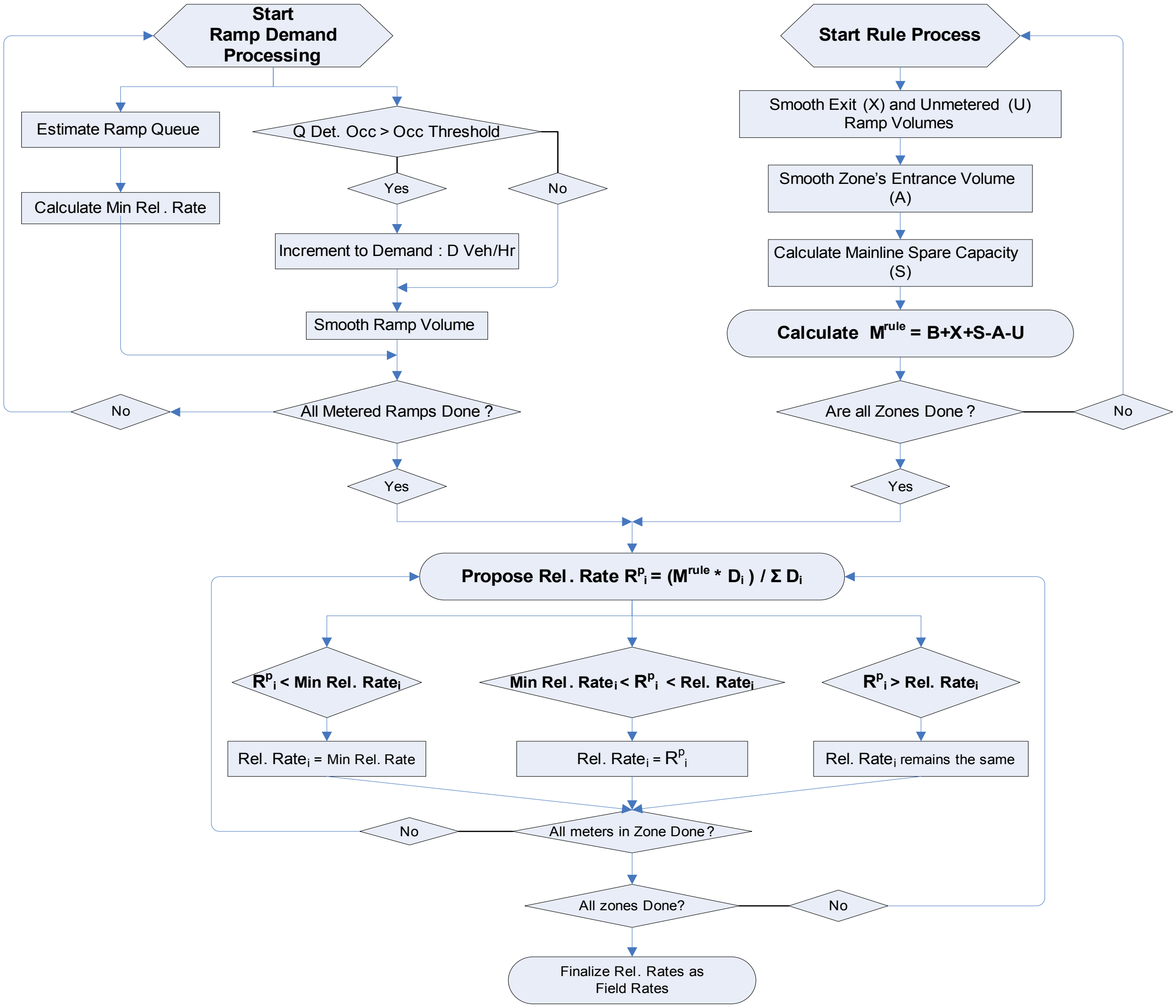


Figure 2.2 Structure of Stratified Zone Metering Algorithm

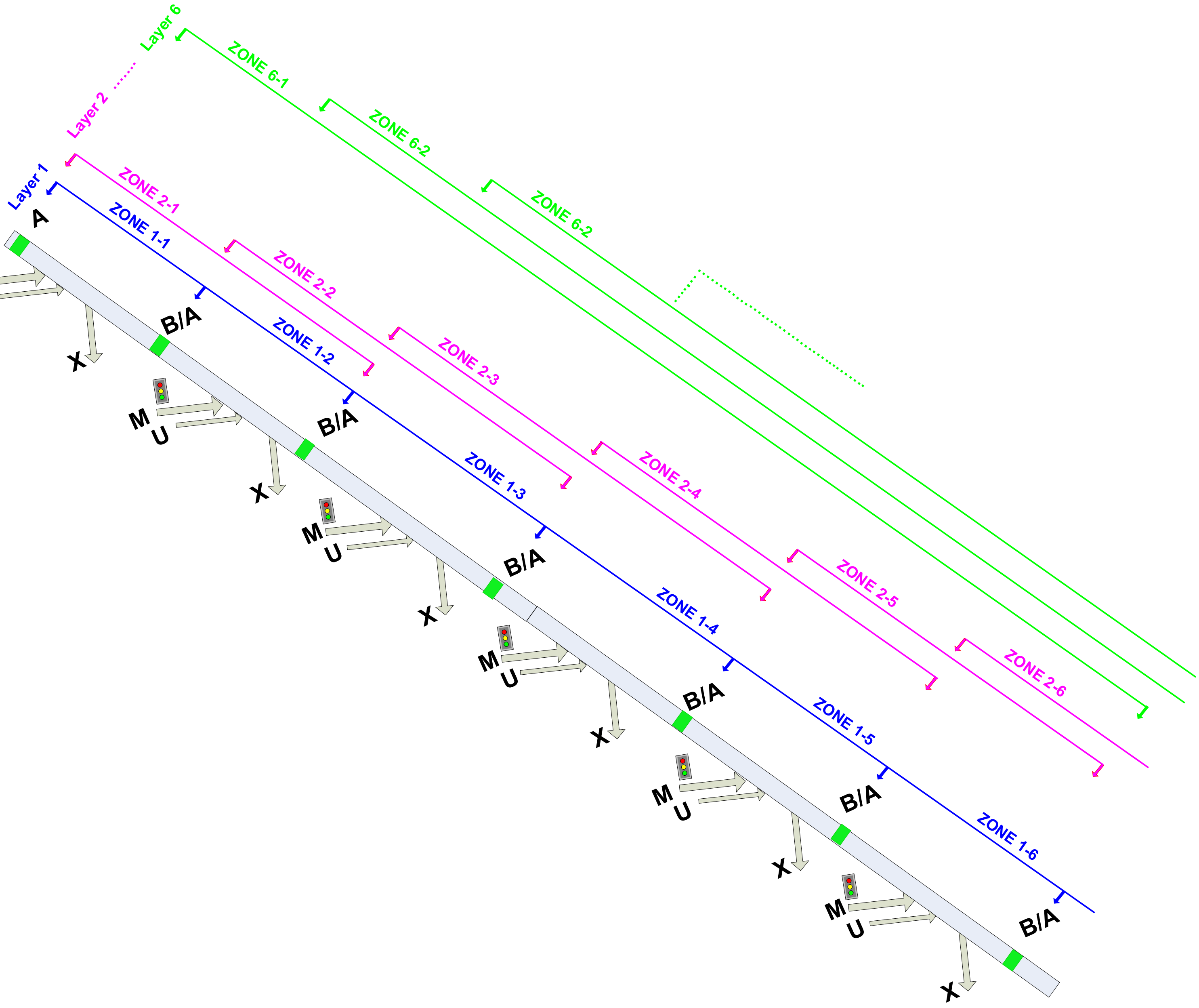


Figure 2.3 Zone-Layer Structure of Stratified Zone Metering

Chapter 3: Microscopic Simulator and its Enhancements

Simulator Overview

AIMSUN is an integral part of GETRAM (Barceló et al., 1994), a simulation environment which consists of a traffic network graphical editor called TEDI, a network database, a module for reading from the network database (Pre-simulator), a module for performing the simulation (Simulator), a module for storing results and a Library of sophisticated API (Application Programming Interface) to emulate any user defined control strategy and other ATMS applications. A detailed description of GETRAM Simulation Environment is beyond the scope of this thesis but can be found in Generic Environment for Traffic Analysis and Modeling, Grau, R., Barcelo, J. and Ferrer, J.L., 1994. Figure 3.1 presents an overall functional structure of AIMSUN and its integration with GETRAM Environment.

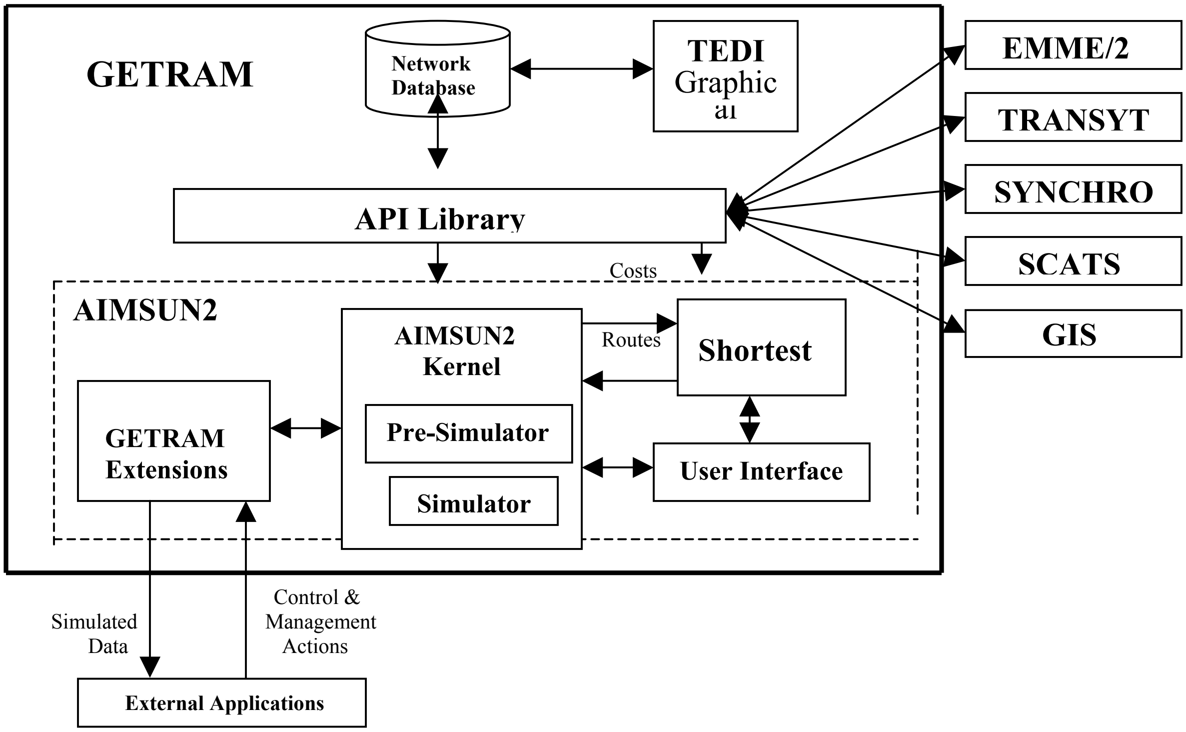


Figure 3.1 Conceptual Structure of AIMSUN

In AIMSUN, simulation time is split into small time intervals called simulation steps and the vehicles are updated according to vehicle behavior models, car following model and Lane changing model. The car following model implemented in AIMSUN is an ad hoc development of the Gipps model

(Gipps, 1986). It was calibrated based on field tests and was further tested on its ability to reproduce macroscopic relationships between fundamental variables. The lane changing behavior in AIMSUM is modeled as a decision process analyzing the necessity of a lane change (to make turns), the desirability of a lane change (to reach desired speeds) and the feasibility for a lane change (to accept a gap). The actual event of a lane change is governed by a Look Ahead model which captures different lane changing motivations observed among the drives. Two zone distances, corresponding to the discretionary and the forced lane changing behaviors, are identified for the sections that end in a turning movement. Vehicles in the first zone distance tend to get closer to a desired lane and attempt to change lanes without affecting the vehicles in the adjacent lanes. Vehicles within the second zone distance force to reach their desired lanes reducing their speeds and thereby affecting the vehicle behavior in adjacent lanes.

Like most microscopic simulators, AIMSUN also generates outputs which are stochastically distributed. In other words, a simulation model does not provide a unique solution to a given problem as it emulates the behavior of a complex system in which randomness is inherent. The random seed is the only parameter related to randomization. This parameter is an integer used as an initial seed in the pseudo-random number generator of sample real numbers uniformly distributed between 0 and 1. These numbers are used to produce different random distributions which are used to define vehicle arrivals, vehicle characteristics, etc. Thus, using the same random seed always generates identical simulation results. Therefore, a simulation study requires multiple simulation runs using different seed numbers so that the median simulation run or the average results of several simulation runs can reflect average traffic condition of a specific scenario. To determine the number of simulation runs, the mean and variance performance MOEs from simulation results need to be calculated.

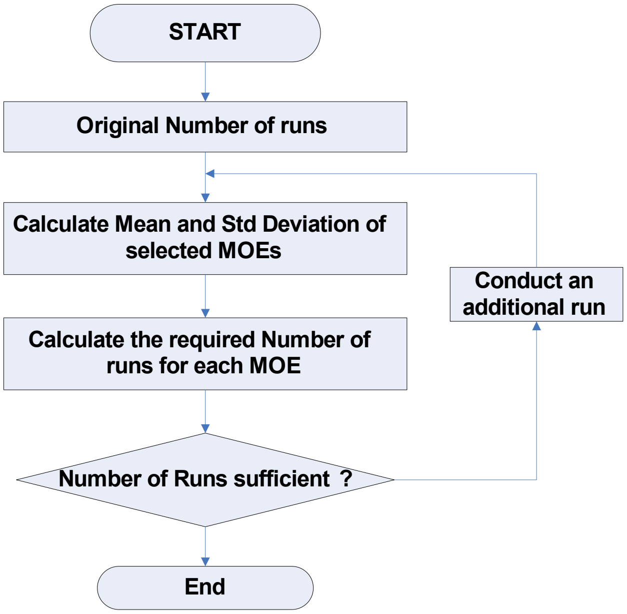


Figure 3.2 Flow chart for the calculation of number of replications

The number of replications *(N)* required in order to obtain a value within k% of the mean with a α% level of confidence is .

$$N = (t_{\alpha/2}\frac{\delta}{\mu\varepsilon})^2$$

Where μ and δ are the mean and standard deviation of the performance measure based on the already conducted simulation runs; ε is the allowable error specified as a fraction of the mean μ; $t_{\alpha/2}$ is the critical value of the t-distribution at the confidence level of 1- α. A 97.5% confidence level and a 2.5% allowable error were used in the calculation. In this study, for each of the three selected performance MOEs the required number of replications are calculated and the maximum of all is selected for the entire experiment. Figure 3.2 presents the steps in the form of a flow chart. It has been determined through this procedure that 10 replications are just more than recommended to attain a confidence level of 97.5%. Thus, the average value of all replications was used as the response for each performance MOE. However, for calibration purposes the random seed that generated the median VHT was selected as the representative condition for calibration.

Simulator Enhancements

AIMSUN provides six high level API functions that are defined in order to enable the communication between the AIMSUN simulation model and a user built Getram Extension Module: GetExtLoad, GetExtInit, GetExtManage, GetExtPostManage, GetExtFinish and GetExtUnLoad.

(1) *GetExtLoad():* It is called when the external application is loaded by AIMSUN

(2) *GetExtInit():* It is called when AIMSUN starts the simulation and can be used to initialize the external application

(3) *GetExtManage* (***floa****t time,* ***float*** *timeSta, float timeTrans,* ***float*** *acicle*): This is called every simulation step at the beginning of the cycle, and can be used to request detector measures, vehicle information and interact with junctions, metering and VMS in order to implement the control logic.

(4) *GetExtPostManage (****floa****t time,* ***float*** *timeSta, float timeTrans,* ***float*** *acicle):* This is called in every simulation step at the end of the cycle.

(5) *GetExtFinish():* It is called when AIMSUN finish the simulation and can be used to clear whatever data structures declared in the external applications

(6) *GetExtUnLoad():* It is called when the external application is unloaded by AIMSUN.

Figure 3.3 graphically depicts the interaction between a GETRAM extension module and AIMSUN simulation model.

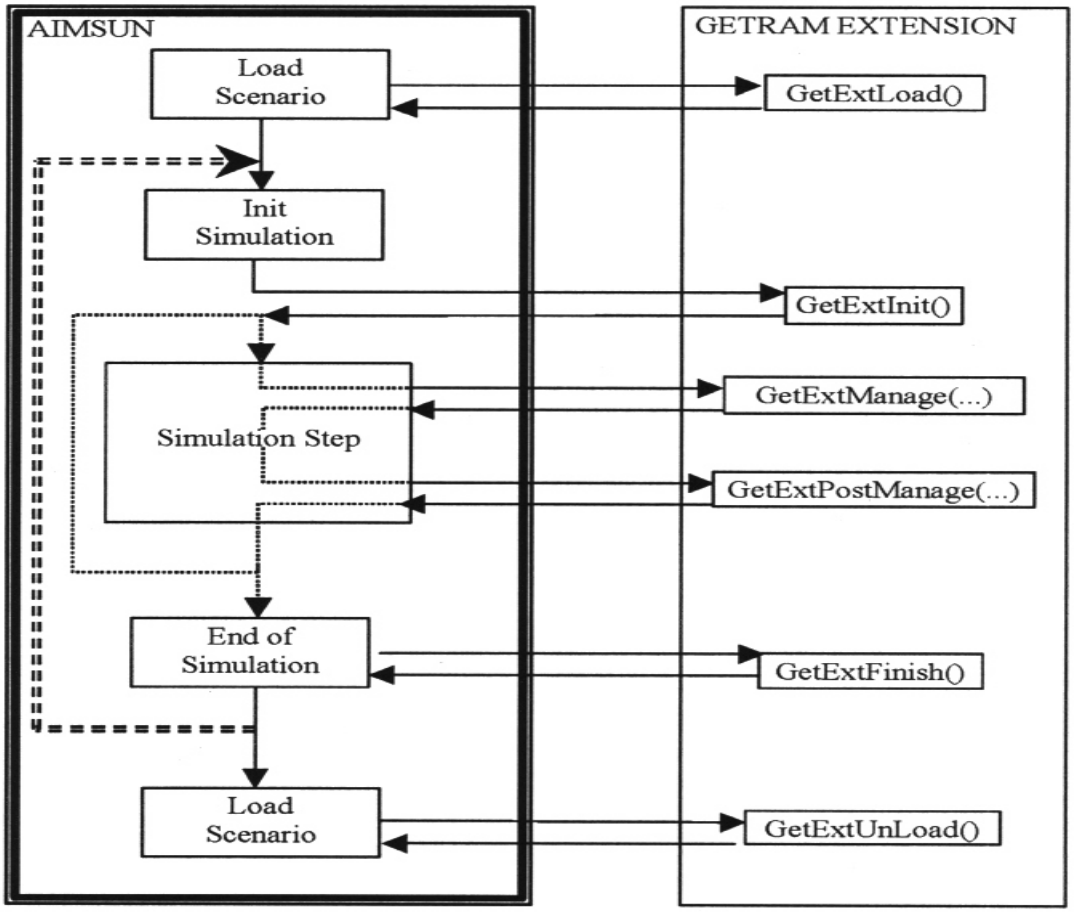


Figure 3.3 Interactions between GETRAM Extension Module and AIMSUN

The two major enhancements required are

Design of the Control Plan Interface

The design of the CPI is better understood by knowing how the traffic control systems operate in real life. The general process involved in the operation of advanced traffic control systems is as follows: the road network is equipped with traffic detectors with specific layout corresponding to the requirements of the control strategy. The detectors supply the necessary real-time traffic data to the control logic, which after suitable processing makes ad-hoc control decisions such as extending the green phase, changing to the red phase, or applying some traffic calming strategies. These decisions are then relayed to the traffic control devices such as traffic lights, VMS or ramp meters for implementation. In order to simulate this process properly, a simulator needs to be capable of modeling the corresponding traffic devices and emulate their functions in a flexible way, and so requires the Control Plan Interface to be capable of:

- Providing the specific runtime traffic measurements to the control logic at the user defined aggregation time intervals and
- Transferring the ad-hoc control decision from the control logic to the simulation model for implementation.

Essentially the CPI can be considered as a higher-level abstraction that encapsulates the appropriate raw API functions, facilitating the interfacing of AIMSUN with external user-defined ramp control logic. In this way, the CPI ensures the isolation of any ramp control logic from specific roadway geometric layout, allowing one ramp control strategy to be easily replaced with another. As a result, the CPI not only helps test different ramp control strategies on the same network within a single simulator, but also facilitates the finding of optimal operational parameters for a specific control plan, which is the primary objective of this study. Figure 3.4 illustrates the relationship between the simulator, CPI and ramp control logic.

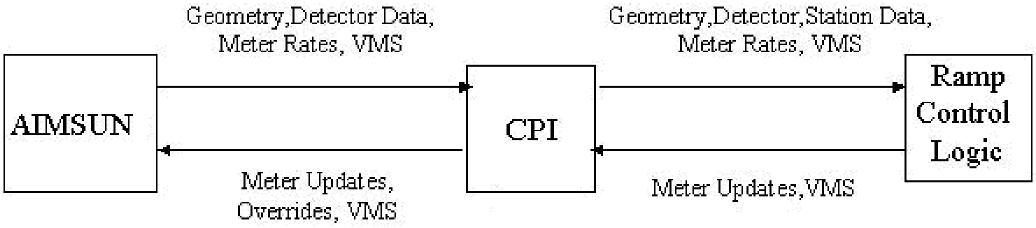
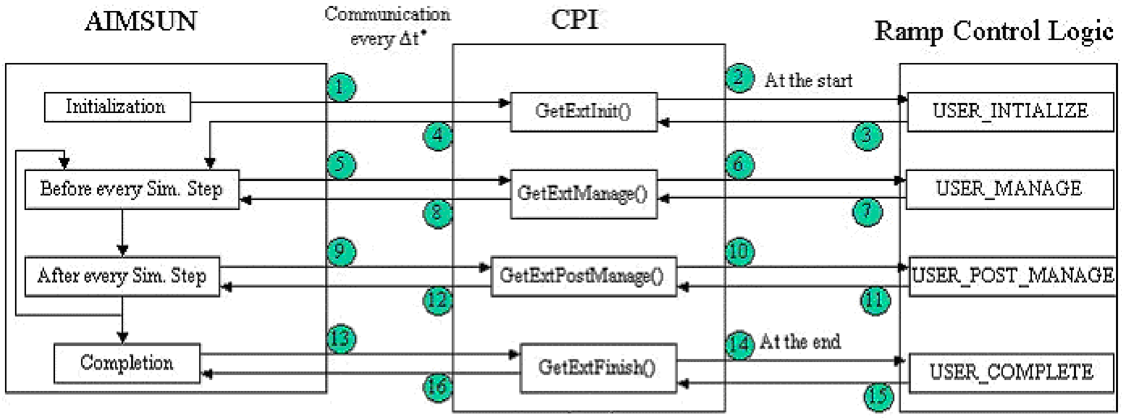


Figure 3.4 Interactions between AIMSUN, CPI, and Ramp Control Logic

Flow of Control in the CPI

The flow of control within the simulator, CPI, and ramp control logic is shown in Figure 3.5. The circles numbered from 1 to 16 represent the steps of the control flowing between the corresponding components. For simplicity, the prefix "circle" is omitted while describing the process.

The first function invoked is GetExtInit. In this function, the input data such as the updating interval for traffic data and ramp control are parsed from an input text file. Appropriate data structure such as the detector maps, station maps and meter maps are declared and initialized in this step (step 1). Next, in the function USER_INITIALIZE the data structures required by the ramp control logic are created and initialized. The default ramp metering rates are returned at this stage (through the step 3 and step 4).



*Δt is simulation step

Figure 3.5 CPI interactions with the Simulator and the Ramp Control Logic

Once the initialization is done, the control is transferred to the function GetExtManage (step 5). In this function the CPI data structures are updated with the runtime simulation data; then the flow of control is passed on to the ramp control logic implemented in the USER_MANAGE function (step 6). The ramp control logic makes decisions for the applicable metering rates to be implemented and returns the ad-hoc decision to the CPI (step 7). Finally, the CPI relays this decision to the simulator for implementation (step 8). After step 8, the control is passed on to the function GetExtPostManage (step 9). This function allows completing whatever tasks necessary. Then the control is transferred to the function USER_POST_MANGE (step 10). Towards the end of the simulation, the function GetExtFinish is called to clear up the data structures defined within the CPI (step 13) while the data structure created for the user-defined ramp control logic is cleared up in the function USER_COMPLETE (step 14).

The Control Plan Interface is developed under the IDE of VC 6.0, using Microsoft Foundation Classes (MFC 4.21). It is in the form of Dynamic Link Library (DLL) that the user can easily integrate to the simulator.

EMULATION OF THE RAMP CONTROL STRATEGY

Having developed the CPI, the further step is to emulate the Mn/DOT's New Statified Zone Metering ramp control, on which the applicability of the optimization methodology will be demonstrated in subsequent chapters. The algorithm is implemented in the simulator by developing the necessary code on top of the CPI. The Visual C++ program has been extensively tested to ensure that the algorithm produced not only the correct final ramp metering rates but also correct output at each and every interim stage of the rates calculation. In order to accurately replicate the control logic, the following two main configuration files are necessary:

Rulefile.txt

In the stratified zone-metering algorithm each segment of the freeway, from a half-mile to three miles in length, constitutes a zone. As these zones within the freeway overlap, the concept of layers has been used in rule processing. The configuration file rulefile.txt provides a sequence of all the detector stations in the same order, as it actually exists on the freeway segment under study. This enables easy identification of all the zones and layers. The file primarily provides the IDs of metered ramps, unmetered stations and exit stations in between two successive mainline stations of the freeway.

The following syntax needs to be maintained in this configuration file:

- The basic format of each line is:

  String_indentifier TAB string TAB string TAB….
- The string identifiers have to be exactly as shown in the table with the order of the lines also being important;
- Each string identifier ends with a colon (:);
- The spacing between the colon and the identifier name can be arbitrary; but it is so chosen that, an indentation is preserved;
- A double asterisk character (‘ ** ’) designates a mainline station entry;

- In case of multiple entries to an identifier, a spacing of one tab between entries is maintained;
- In case of no entry to an identifier, a blank line remains;
- In the last line of rulefile.txt, '###END_OF_RULEFILE###' is used to mark the end of file.

A sample rulefile.txt below shows the syntax to be followed:

Sample configuration file rulefile.txt

```
**MAINLINE STATION  :   428
Metered Ramps       :
Unmetred station    :
Exit station        :   1039
**MAINLINE STATION  :   429
Metered Ramps       :   3A2    3A3
Unmetred station    :   1349
Exit station        :   1117   1365
**MAINLINE STATION  :   430
… …
… …
###END_OF_RULEFILE###
```

Ramps.txt:

The ramps configuration file provides the IDs of the detectors on the on-ramps, ramp length, ramp type and ramp name. The sequence of these entries is:

1. Ramp name:e.g., 36th street;
2. Ramp type:L represents local access ramp while F represents freeway to freeway ramp;

3. Queue station:TH62EB
4. Passage station: Detector ID as in freeway section e.g., 1358
5. Ramp length: Distance between queue detector and the metering pole (feet)

- The entries should be as shown below:

  String identifier: string TAB string TAB string TAB string TAB string

- No spacing after the colon;

- In case of no entry being appropriate, “none” is used as the string;

- In case of no queue detector, the ramp length needs to be set to 1 foot;

A sample ramp.txt below shows the syntax to be followed:

Sample configuration file ramp.txt

```
Ramp_name/type/queue_station/passage_station/ramp_length:Valley View Rd
3A1	L	ValleyView	1355	350
Ramp_name/type/queue_station/passage_station/ramp_length:T.H.62 E.Bound
3A2	F	TH62EB		1358	296
Ramp_name/type/queue_station/passage_station/ramp_length:T.H.62 W.Bound
3A3	F	TH62WB		1361	1050
Ramp_name/type/queue_station/passage_station/ramp_length:Cedar Lake Rd
3B6	L	none	1928	1
```

Evaluation Methodology

Performance Measures of Effectiveness

Depending on the evaluation objective, the following Measures of Effectiveness (MOE) are selected. These MOEs fall into three general categories: freeway, ramp, and system (i.e., freeway and ramp) performance. The specific measures of effectiveness within each category are:

(1) Freeway Performance MOE
   a) Freeway Total Travel Time: Total travel time accumulated by all the vehicles while traveling on the freeway mainline (vehicle-hours) within a specified period of analysis;
   b) Freeway Total Delay: Total delay time accumulated by all the vehicles while traveling on the freeway mainline (vehicle-hours) within a specified period of analysis;
   c) Average Freeway Delay: Average delay time per vehicle while traveling on the freeway mainline (minutes/vehicle);
   d) Average Freeway Speed: Space mean speed for vehicles serviced by the freeway mainline (miles/hour);
   e) Total Number of Freeway Stops: Total number of stops experienced by all the vehicles while traveling on the freeway mainline;
   f) Number of Stops per vehicle: Average number of stops per vehicle while traveling on the freeway mainline;

2) Ramp Delay/Queue MOE
   a) Ramp Total Travel Time: Total travel time accumulated on all metered ramps (vehicle-hours);
   b) Ramp Total Delay: Total delay time accumulated on all metered ramps (vehicle-hours);
   c) Average Ramp Delay: Ramp Total Delay averaged over ramp volumes (minutes/vehicle);
   d) Max Ramp Wait Time: Maximum wait time experienced by vehicles while traveling the ramp under study (minutes);
   e) Average Ramp Wait Time: Average wait time per vehicle while traveling the ramp under study (minutes);
   f) Max Ramp Queue Size: Maximum number of vehicles in queue on the ramp under study;
   g) Average Ramp Queue Size: Average number of vehicles in queue on the ramp under study;

3) System Performance MOE
    a) Total System Travel Time: Total travel time accumulated by all vehicles (vehicle-hours) ;
    b) Total System Delay: Total delay time accumulated by all vehicles (vehicle-miles);
    c) Total Fuel Consumptions: Total fuel consumed in gallons;
    d) Total Pollutant Emissions: Total emissions in kilograms for oxycarbite (CO), oxynitride (NO_x) and hydrocarbons (HC), respectively.

Because delay can be defined in many different ways, a clarification is in order. Specifically, in this study, travel delay is defined as the time difference between the desired and actual travel time of a vehicle. In this definition, desired travel time is determined (by the simulator) from both the freeway speed limit and driving characteristics of each individual vehicle.

Test Sites and Data Acquisition

Two sites, as shown in Figure 3.6, are selected for the evaluation study with flow properties and geometric characteristics representative of Twin Cities freeways.

The first selected test site is a 12-mile segment of Trunk Highway 169 northbound (TH169 NB), starting from the I-494 interchange and ending on 63rd Avenue North. This site is a circumferential freeway traversing the Twin Cities west metropolitan region. It includes 10 weaving sections, 4 HOV by-pass ramps, 24 entrance ramps (17 metered) and 25 exit ramps. Among the metered ramps, there are 15 local access ramps and 2 freeway-to-freeway ramps connecting TH 62 and I-394 respectively. The upstream and downstream boundaries are usually uncongested. In comparison with the next site selected, TH169NB is of medium geometric complexity and carries relatively low volumes of traffic.

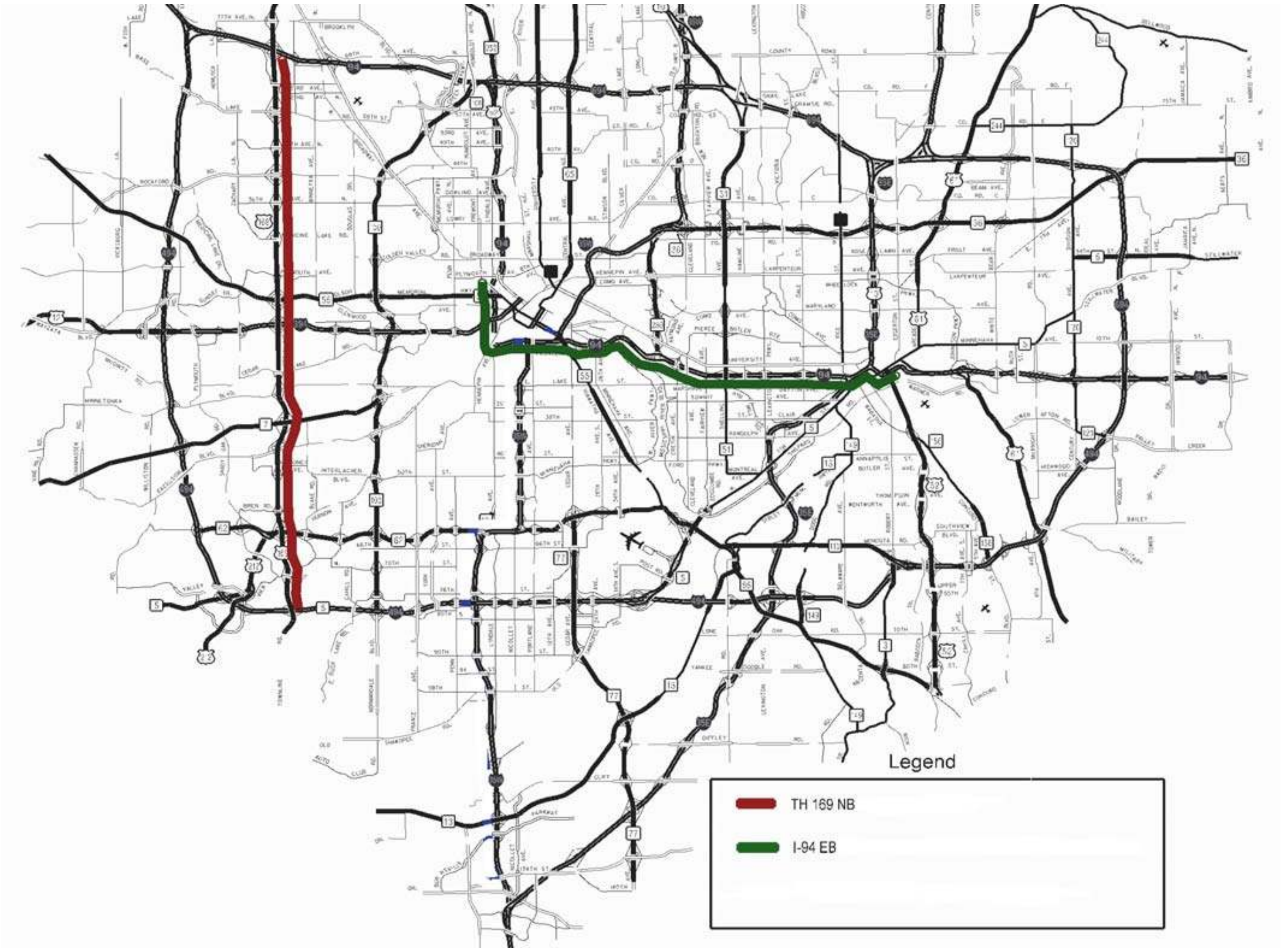


Figure 3.6 Selected Test Sites: TH169NB and I94EB

The second test site is the I-94 eastbound (I-94EB) freeway from I-394 to the 9th Street.

This site falls into the category of CBD connector, since it connects the Minneapolis and St. Paul downtown business districts and carries heavy volumes of traffic. It is about 11 miles in length, containing 6 weaving sections, 3 lane-drop sections, 19 entrance ramps (four unmetered), and 14 exit ramps. The upstream and downstream ends are uncongested. The unique feature of this site is that I-94 merges with I-35E near downtown St. Paul, which adds to the geometric complexity yet provides an opportunity to study the interaction between two freeways.

The Twin Cities traffic detection/surveillance system consists of over 4,000 loop detectors and 300 closed circuit television (CCTV) cameras. This system provides traffic volume and occupancy measurements every 30 seconds as well as visual monitoring of real-time traffic flow. The demand data required in the research was retrieved and extracted from data archives of this system.

Specifically, the traffic demand data needed in the study are (1) traffic composition and entrance volumes; (2) turning percentages of mainline flow at exit ramps. In order to reproduce the prevailing demand patterns without increasing computational complexities, the updating time-slice for the selected traffic demand is determined to be 5 minutes, i.e., both entrance volumes and turning percentages are updated every 5 minutes.

The traffic composition data are not directly available from Mn/DOT traffic detection/surveillance system. In this study, the data were extracted from CCTV videos records, supplemented by in-person field-collection. Furthermore, the 5 minutes time-sliced entrance volumes were retrieved and extracted from queue detector data archives with the help of the Traffic Demand Generation Utility described in earlier section.

Turning percentages of the mainline volumes at exit ramps are needed by the micro-simulator to replicate the actual traffic flow process since Origin/Destination information is not available. In the study, each turning percentage is determined from the ratio of mainline detector volume to exit detector volume, i.e., the turning percentage of the mainline flow at the exit ramp is computed as $P = \frac{V_{exit}}{V_{mainline}}$, where P represents the turning percentage of mainline volume exiting from the off-ramp; V_{exit} and $V_{mainline}$ represent the volume recorded by exit ramp detector and mainline detectors during the prescribed time interval.

Following the procedure described above, six test days during the shutdown period were selected for the simulation experiments, i.e., Nov 8th, Nov 13th and Nov 27th, 2000 for TH169NB; Oct 26th, Nov 1st, Nov 27th, 2000 for I94EB. The dates were specifically selected during the ramp meter shutdown period to ensure the calibrated simulation models have no systematic bias to a particular set of control parameter values. Afternoon peak was selected as the test sites experience more severe congestion at that time. These test days not only represented varying traffic conditions from moderate to heavily congested, but also, as mentioned earlier, provided uniform traffic conditions for comparing different ramp control strategies. The simulation period for each test day is PM hours, from 14:00 to 20:00 (the metered period is from 15:00 to 18:00); this covers the time prior to and after congestion.

Simulation Model Calibration

Once the geometric and traffic data were used to build the simulation models of the test sites, the next step was to calibrate them. Simulation model calibration is the process of obtaining a good match between actual and simulated fundamental measurements (e.g., Flow and Speed) by fine tuning the global and local parameter of the microscopic simulator. In this study the two-stage calibration methodology proposed in Hourdakis and Michalopoulos, 2003 was followed.

In the first stage, the initial model parameters used were based on values found in the literature for vehicle characteristics and the posted speed limits on each of the freeway sections. Based on these model parameters and on demand information of one day for each site, a "first guess" scenario was formed. This "first guess" was calibrated by comparing real mainline volumes with simulated ones. After approximately 300 iterations per site, a satisfactory match was achieved based on statistical tests. The comparison statistics used were *Root Mean Square Error*, *Root Mean Square Absolute error, Mean error, Mean Absolute Error, Correlation coefficient* and *Theil's Inequality Coefficient* or U-statistic (Pindyk and Rubinfeld, 1991). The second stage aimed at calibrating the model so that the speed (calculated from volume/occupancy from the real data) on every mainline detector station achieves a good match between simulation and real measurements. This phase required approximately 100 iterations. The same statistics were used as in the first stage.

At the end of the calibration process, satisfactory statistical match was achieved (based on volume and speed). For instance, by comparing actual and simulated volumes on mainline detector stations, the correlation coefficient (r^2) was very high ranging from 0.90-0.98 at both test sites, while similar scores were obtained for other test metrics (Thiel's coefficients, etc) and speed contours.

Chapter 4: RESULTS

The primary aim of the new strategy is to prevent excessive ramp queue and wait times that occurred under the ZONE algorithm. In order to determine if this objective is met as well as whether the new strategy is beneficial as compared to the No Control alternative, the simulation results are summarized on the basis of two comparisons: Stratified Zone Metering Strategy vs. No Control alternative (Table 4.1) and Stratified Zone Metering Strategy vs. pre-shutdown ZONE algorithm (Tables 4.2 and 4.3).

Stratified Zone Metering Strategy vs. No Control

The comparison results of Stratified Zone Metering Strategy vs. No Control alternative are summarized in Table 4.1. This table presents the MOEs' percentage change with Stratified strategy, taking No Control as the base case, i.e., a positive percentage change of an MOE indicate this MOE increased with Stratified Zone Metering Strategy in comparison to the No Control alternative and vice versa. Each table includes results for both test sites (TH169NB and I94EB) and all six test days (three days each site).

As Table 4.1 suggests, under the Stratified Zone Metering Strategy, **freeway delay** was reduced when compared to the No Control alternative. On typical days, the reduction varies from 8-14%, depending on geometric features of the freeway and demand conditions. For example, on TH169NB, which has relatively simple geometry and moderate traffic, freeway delay reductions are in the order of 14% on typical days; while on I94EB, which is a CBD freeway with complex geometry and relatively heavier demand, the freeway delay reduction became less pronounced, i.e., about 8% on typical days. Furthermore, on abnormal days when severe freeway congestion occurred, Stratified Zone Metering Strategy cannot prevent further deterioration of freeway flow; freeway delay reduction becomes negligible for both sites. From Table 4.1 it is also evident that for both test sites**, traffic delay evaluated at system level** (i.e., ramp delay plus freeway delay) exhibits a compound trend, i.e., system delay could increase or decrease with Stratified Zone Metering Strategy in comparison to the No Control alternative. For example, on TH169NB, system delays reduced by 2.1-3.6% on typical days but increased by 6.7% during the highly congested day; while on I94EB, system delays increased for all test days. These findings suggest that for freeway with medium congestion level and fairly simple geometry (e.g., TH169 NB), Stratified Zone Metering Strategy could save system delays marginally; while for freeway with rather complex geometry and heavy traffic (e.g. I94EB), system delay might degrade to the No Control alternative.

Categories	% Change [1]		TH169NB			I94EB		
			Nov08	Nov13	Nov27 [2]	Oct26 [3]	Nov1	Nov27
Freeway MOEs (Mainline)	**Total Num of Stops**		-24%	-19.3%	-0.6%	-2%	-7.5%	-9%
	Num of Stops per Vehicle		-24%	-19.3%	0.5%	-2%	-7.5%	-9%
	Total Freeway Travel Time (veh-hours)		-7%	-6.7%	-1.5%	-1%	-4%	-3.6
	Total Freeway Delay (veh-hours)		-14%	-13.5%	NG [4]	-2%	-8%	-8.4%
	Avg Freeway Delay (veh-hours)		-14%	-13.5%	NG	-2%	-8%	-8.4%
	Average Speed (mile/hour)		+7%	+6.7%	+2.5%	+1.5%	+4.4%	+ 5.4%
System MOEs	**Total Travel Time (veh-hours)**		+1.7%	+0.5%	+5.7%	+6%	+4.3%	+7.5%
	Total Delay (veh-hours)		-2.1%	-3.6%	+6.7%	+8%	+4.6%	+11.4%
	Fuel Consumption (Gallons)		-6%	-3.6%	+13%	+1.2%	-1.4%	+0.2%
	Pollutant Emissions(kgs)	**CO**	-3%	-8%	+2.6%	+3.5%	+0.4%	+2%
		HC	-1%	-0.5%	+2.1%	+4%	+1.1%	+3.8%
		NOx	-4%	-3.2%	+3.1%	+2.6%	NG	-1.8%

[1] Base of the comparison is no control

[2] Most severely congested day on TH169NB

[3] Most severely congested day on I94EB

[4] Less than 0.5%

Table 4.1 Comparison of Stratified and No Control Alternatives for Metering Period (3:00pm – 6:00pm)

% Change [1] Categories			TH169NB			I94EB		
			Nov08	Nov13	Nov27	Oct26	Nov1	Nov27
Freeway MOEs (Mainline)	**Total Num of Stops**		+1062%	+1406%	+1326%	+270%	+187%	+242%
	Total Freeway Travel Time (veh-hours)		+73%	+58%	+137%	+37%	+25%	+39%
	Total Freeway Delay (veh-hours)		+421%	+342%	+532%	+202%	+138%	+189%
	Avg Freeway Delay (veh-hours)		+387%	+328%	+512%	+201%	+138%	+184%
	Average Speed (mile/hour)		-39%	-37%	-58%	-27%	-19%	-17%
Ramp MOEs	**Total Ramp Travel Time (veh-hours)**		-71%	-78%	-71%	-58%	-57%	-26%
	Total Ramp Delay (veh-hours)		-74%	-81%	-73%	-64%	-64%	-63%
	Average Ramp Delay (min/veh)		-77%	-82%	-74%	-66%	-66%	-63%
System MOEs	**Total Travel Time (veh-hours)**		+13%	+6.3%	+51%	+27%	+14.7%	+8.2%
	Total Delay (veh-hours)		+54%	+36%	+133%	+70%	+44.7%	+30.8%
	Fuel Consumption (Gallons)		+118%	+68%	+144%	+76%	+48%	+46%
	Pollutant Emissions(kgs)	**CO**	+42%	+25%	+59%	+50%	16%	+21%
		HC	+26%	+14%	+40%	+42%	+11%	+16%
		NOx	+60%	+37%	+74%	+59%	+22%	+28%

[1] Base case of the comparison is ZONE metering strategy

Table 4.2 Comparison of Stratified and ZONE Control for Metering Period (3:00pm-6:00pm)

MOE Ramps	Avg. Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering
Valley View Road	0.36	0.18	2.87	1.55	11	6	3	1	18	18
TH 62 EB	0.59	0.24	2.08	1.33	18	7	4	2	16	18
TH62 WB	0.89	0.13	5.37	0.73	25	4	6	1	38	10
Bren Road	2.19	0.23	5.58	1.32	59	6	14	1	19	17
Lincoln Drive	1.87	0.20	10.30	0.85	17	2	4	1	22	6
Excelsior Blvd	3.95	0.67	11.45	4.33*	96	18	23	4	31	28
TH 7	1.07	2.21	8.38	7.63*	24	51	5	12	33	35
36th Street	0.15	0.23	0.38	0.70	2	3	1	1	5	6
Minnetonka Blvd	0.60	0.23	4.72	0.98	7	3	2	1	14	7
Cedar Lake Road	0.16	0.15	0.48	0.38	1	1	1	1	3	3
I-394 EB	1.09	0.21	4.13	1.05	22	4	5	1	27	10
I-394 WB	4.66	0.33	9.27	1.82	152	11	36	2	54	22
Betty Crocker Dr	7.54	0.28	14.83	1.02	82	4	19	1	33	11
TH 55 EB	7.56	0.22	16.27	0.55	86	3	20	1	40	6
TH55 WB	9.86	0.22	22.17	0.63	120	3	28	1	47	6
Plymouth Ave	3.78	0.75	7.55	2.95	53	15	12	3	17	16
Medicine Lake Rd.	4.28	1.36	8.42	5.08*	73	23	17	5	25	23

* The maximum allowed ramp wait time is violated.

Table 4.3 Ramp MOE's on TH169NB, Nov 13, 2000

For both sites as well as all test days, freeway **Total Travel Time** is reduced with Stratified Zone Metering Strategy as compared to the No Control alternative. On TH169NB, freeway travel time is reduced by about 7% on typical days while during the highly congested day, reduced by about 1.5%; on I94EB, freeway travel time is reduced by about 4% on typical days, but during the highly congested day, reduced by only 1%. In both sites and all test days, system total travel time increased with Stratified Zone Metering Strategy when compared to the No Control alternative, e.g., on TH169NB, system total travel time increased by 0.5%-5.7%; while on I94EB system total travel time increased by 4.3%-7.5%. This result means the savings in freeway total travel time were offset by the increase in ramp travel time induced by the control.

Due to the reduced freeway travel time, **Average Freeway Speed** increased with the Stratified Zone Metering Strategy. As shown in Table 4.1, average freeway speed on TH169NB increased by about 6.7-7% on typical days and increased by 2.5% during the high demand day. This trend was also observed in I-94EB, where freeway speed increased by about 4.4-5.4% and 1.5%. In addition, the Stratified strategy is still effective in smoothing out freeway flows as compared to the No Control alternative. This is illustrated in Figure 4.1. In this figure, the density pattern of Th169NB on Nov 13th, 2000, effected by ZONE Control, Stratified Control and No Control respectively are plotted. As can be seen clearly in this figure, freeway density variations are smoother under the Stratified control.

As indicated in Table 4.1, the Stratified Zone Metering Strategy reduced the total number of mainline stops for both sites on all test days. The reduction varies from 19%-24% on TH169NB and 7.5-9% on I94EB. This implies a potential decrease of freeway crash rates under the new strategy, as compared to No Control.

Table 4.1 also illustrates that the Stratified strategy has mixed influence on **fuel consumption** and **pollutant emissions**. For example, on Th169NB, the total fuel consumption on typical days decreased by 3.6-6% with the Stratified strategy but increased by 13% during the high demand day. Similarly, on typical days, pollutant emissions on Th169NB decreased with the Stratified strategy by 3%-8%; but increased on the high demand day by 2-3% as compared to No Control. Similar trends were also observed on I94EB.

These mixed results can be expected. Reduced congestion on the freeway allows for greater fuel efficiency and reduced emissions on the mainline, but vehicles queued at ramp meters have increased rates of fuel consumption and emissions. The combination of the reduced rate on freeway and increased rate on the ramps determines the final effects of ramp control on fuel consumption and pollutant emissions.

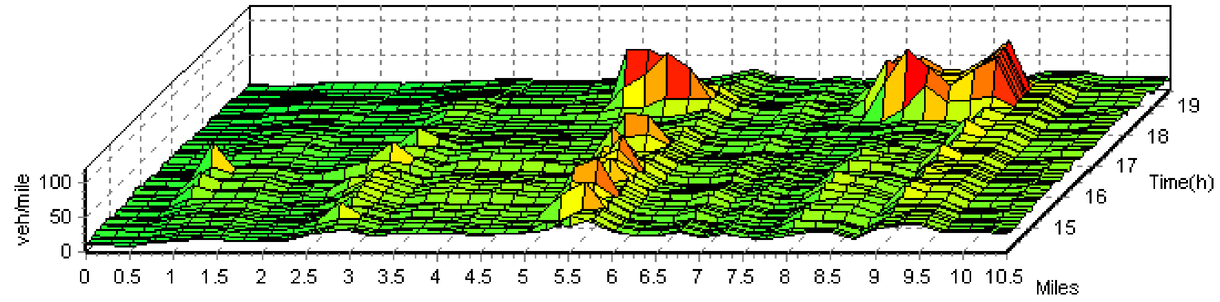
Stratified Zone Metering Strategy vs. ZONE Metering Strategy

Comparison Results of Stratified Zone Metering Strategy vs. ZONE Metering Strategy are summarized in Tables 4.2 and 4.3. Table 4.2 presents MOE percentage change (during the metering period) with the Stratified strategy taking the ZONE strategy as the base case. Table 4.3 presents the effects of Stratified Zone Metering Strategy on ramp waiting time and ramp queues of TH169NB on Nov 13th, 2000 (Tables summarizing other days and sites depict similar findings and hence for brevity are not presented in this preliminary report but will be included in the Final project report).

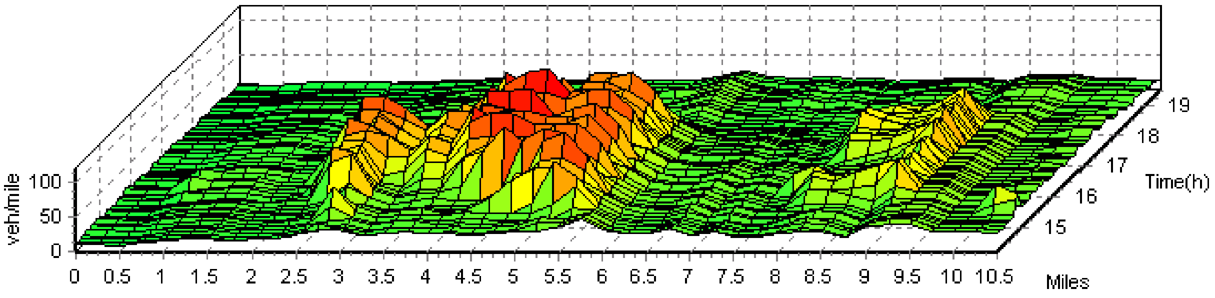
As indicated in Table 4.2, under the Stratified strategy, **ramp delays** are significantly reduced on both sites and all test days as compared to the ZONE algorithm. Specifically, on TH169NB, ramp delays are reduced by 73% to 81%; while on I94EB, this reduction is in the order of 64%. On the other hand, the reduced ramp delay is at the expense of increased mainline delay. As revealed in Table 4.2, on TH169NB, **mainline delay** increased by 342-532%; while on I94EB mainline delay increased by 138-202%. Furthermore, the increase in mainline delays more than offset the saving in ramp delays, leading to an increased system delay, e.g., on TH169NB, system delays increased by 36%- 113% when compared to the ZONE algorithm; while on I94EB, this increase ranges from 30.8%-70%.

Under the Stratified Zone Metering Strategy, **ramp total travel time** was considerably reduced as compared to the ZONE algorithm for both sites and all test days. On TH169NB, the reduction ranges from 71%-78% while on I94EB, 26%-58%. It is also seen in Table 4.3 that freeway total travel time increased for both sites and all test days, e.g., on TH169NB, freeway total travel time increased by 58%-137% while on I94EB, freeway total travel time increased by 25%-39%. Anther important fact revealed from Table 4.2 is that system (freeway and ramp) total travel time increased for both sites and all test days with the Stratified strategy when compared to the ZONE strategy. For example, on typical days, system total travel time increased by 6.3 %-13% on TH169 and 8.2%-14.7% on I94EB.

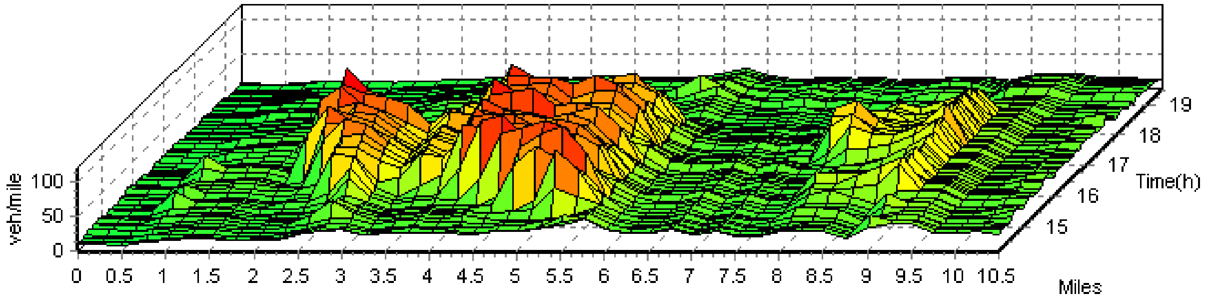
Table 4.2 also suggests that mainline **Average Speed** under the new strategy dropped on both sites and all test days when compared to the ZONE algorithm. Specifically, on typical days, average freeway speed dropped by 37%-39% on TH169NB and 17%-19% on I94EB. It is also found that under the Stratified strategy, freeway traffic was less smooth than under the ZONE strategy. This is illustrated in Figure 4.1. As clearly demonstrated in this figure, the ZONE control smoothed out freeway traffic more effectively during the controlled period than the Stratified control.



Freeway Density Pattern: ZONE Control



Freeway Density Pattern : Stratified Control



Freeway Density Pattern: No Control

Figure 4.1 Density Patterns: TH169NB on Nov 13th, 2000

As shown in Table 4.2, under the Stratified control, total number of **freeway stops** increased for both sites and all days, as compared to the ZONE control. On TH169NB, the increase ranges from 1062%-1426%; while on I94EB, the increase ranges from 187%-270%. This implies a potential increase of freeway crash rate with the Stratified control when compared to the ZONE metering strategy.

As revealed by Table 4.2, under the Stratified control, **fuel consumption** increased for both sites and all days when compared to the ZONE control. Specifically, on TH169NB, the increase ranges from 68%-144% and on I94EB, the increase ranges from 46%-76%. Table 4.2 also indicates that under the Stratified control, **pollutants emissions** increased for both sites and all days when compared to the ZONE control. Specifically, on TH169NB, CO increased by 25%-59% , HC increased by 14%-40% and NOx increased by 37%-74%; while on I94EB, CO increased by 16%-50% , HC increased by 11%-42% and NOx increased by 22%-59%.

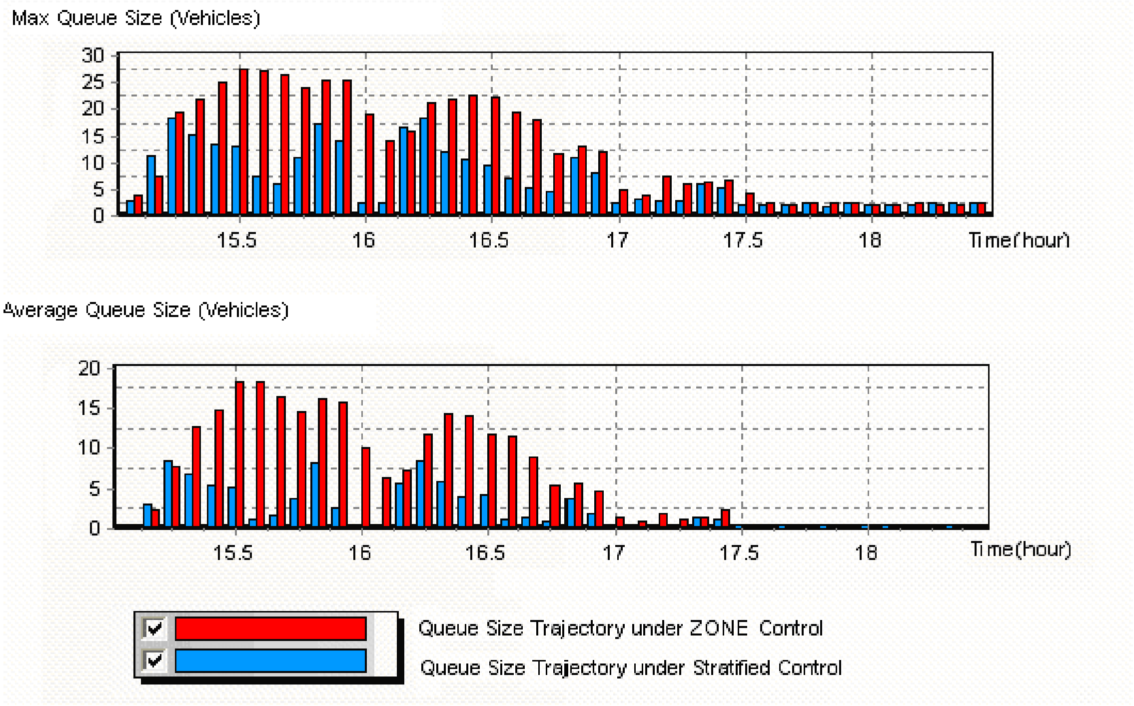


Figure 4.2 Ramp Queue Size Trajectories: Stratified vs. ZONE Control (TH62EB Ramp of TH169NB, Nov 8th, 2000)

Table 4.3 summarizes the effects of the Stratified Zone Metering Strategy on ramp wait times and ramp queue size. As indicated in this table, the Stratified strategy is very effective in keeping ramp wait times below the prescribed threshold (i.e., 2 minutes for freeway to freeway ramp, 4 minutes for local access ramp) and dissipating excessive ramp queues. For example, under the ZONE control, Betty Crocker Drive Ramp's max waiting time is 14.83 minutes; while under the Stratified control, the max waiting time is reduced to 1.02 minutes. Meanwhile, the maximum queue length is reduced from 33 vehicles to only 11 vehicles.

Another interesting observation is that the new strategy evens out big swings of queue and substantially reduces ramp queue sizes. This is demonstrated in Figure 4.2. This figure illustrates the time-dependent queue size trajectory of TH62 EB Ramp. As shown in the figure, the Stratified control not only effectively reduced both average and maximum queue length, but also evens out big fluctuations of the queue size.

CONCLUDING REMARKS

As the simulation results suggest, the Stratified ramp control meets its objective of keeping ramp delays below the predetermined maximum threshold by relaxing the over-restrictive metering rates dictated by the ZONE ramp control algorithm. However, the emphasis on limiting the ramp wait times below an upper bound shifts ramp delays to the freeway mainline and degrades the quality of the freeway flow, as evidenced by increased freeway delays, increased number of stops and increased freeway speed/density variability when compared to the ZONE ramp control strategy. In spite of this, the Stratified ramp control strategy is still beneficial when compared to the No Control alternative in terms of improving freeway performance, i.e., it reduces freeway travel time and delay, increases freeway speed, smoothes freeway flow and reduces number of stops. However, these improvements are not substantial at least under heavier congestion, i.e., the Stratified ramp control strategy is marginally better than No Control. In this situation, ramp demand exceeds freeway capacity and the effectiveness of ramp metering is mostly achieved through averaged entering ramp volumes over an extended time span and more efficient merging.

Furthermore, system delay, system travel time as well as fuel consumption and pollutant emissions under the Stratified control are unpredictable. These MOEs may improve, or degrade as compared to No Control, depending on the freeway geometry and demand patterns. This suggests that there is a need for better trade-off analysis between freeway efficiency and reduced ramp delay. For example, unless practical reasons dictate otherwise, prior to field implementation one needs to determine the most suitable threshold of maximum ramp wait times using a methodology similar to the one presented here. Alternatively, the possibility of employing different threshold values during the control period or at each individual ramp merits consideration. Determining the optimal values of the control parameters including the maximum ramp wait times is the subject of another study currently under way. Preliminary results have revealed that both freeway and system performance of Stratified Control can be substantially improved if the parameters are optimized off-line and some compromise on the maximum wait times is acceptable.

Before concluding it should be pointed out that the ZONE metering strategy is still superior if only the system or freeway performance is important. This is not a surprising result but given the equity questions raised in recent years, it is becoming increasingly evident that practicing engineers will have to take into account the balancing issues and perform evaluations and fine tuning before, during and after deployment using more advanced tools and methods rather than by trial and error.

All Evaluation Tables

Table 1.5 General Measures of Effectiveness: TH-169NB Nov 8th, 2000, 14:00-20:00
Table 1.6 General Measures of Effectiveness: TH-169NB Nov 8th, 2000, 15:00-18:00
Table 1.7 Ramp Measures of Effectiveness : TH-169NB Nov 8th, 2000, 15:00-18:00

Table 1.8 General Measures of Effectiveness: TH-169NB Nov 13th, 2000, 14:00-20:00
Table 1.9 General Measures of Effectiveness: TH-169NB Nov 13th, 2000, 15:00-18:00
Table 1.10 Ramp Measures of Effectiveness : TH-169NB Nov 13th, 2000, 15:00-18:00

Table 1.11 General Measures of Effectiveness: TH-169NB Nov 27th, 2000, 14:00-20:00
Table 1.12 General Measures of Effectiveness: TH-169NB Nov 27th, 2000, 15:00-18:00
Table 1.13 Ramp Measures of Effectiveness : TH-169NB Nov 27th, 2000, 15:00-18:00

Table 1.14 General Measures of Effectiveness: I-94EB Oct 26th, 2000, 14:00-20:00
Table 1.15 General Measures of Effectiveness: I-94EB Oct 26th, 2000, 15:00-18:00
Table 1.16 Ramp Measures of Effectiveness : I-94EB Oct 26th, 2000, 15:00-18:00

Table 1.17 General Measures of Effectiveness: I-94EB Nov 1st, 2000, 14:00-20:00
Table 1.18 General Measures of Effectiveness: I-94EB Nov 1st, 2000, 15:00-18:00
Table 1.19 Ramp Measures of Effectiveness : I-94EB Nov 1st, 2000, 15:00-18:00

Table 1.20 General Measures of Effectiveness: I-94EB Nov 27th, 2000, 14:00-20:00
Table 1.21 General Measures of Effectiveness: I-94EB Nov 27th, 2000, 15:00-18:00
Table 1.22 Ramp Measures of Effectiveness : I-94EB Nov 27th, 2000, 15:00-18:00

Figure 1.12 TH-169: Mainline Speed Variation Nov 8th, 2000
Figure 1.13 TH-169: Mainline Speed Variation Nov 13th, 2000
Figure 1.14 TH-169: Mainline Speed Variation Nov 27th, 2000

Figure 1.15 I-94: Mainline Speed Variation Oct 26th, 2000
Figure 1.16 I-94: Mainline Speed Variation Nov 1st, 2000
Figure 1.17 I-94: Mainline Speed Variation Nov 27th, 2000

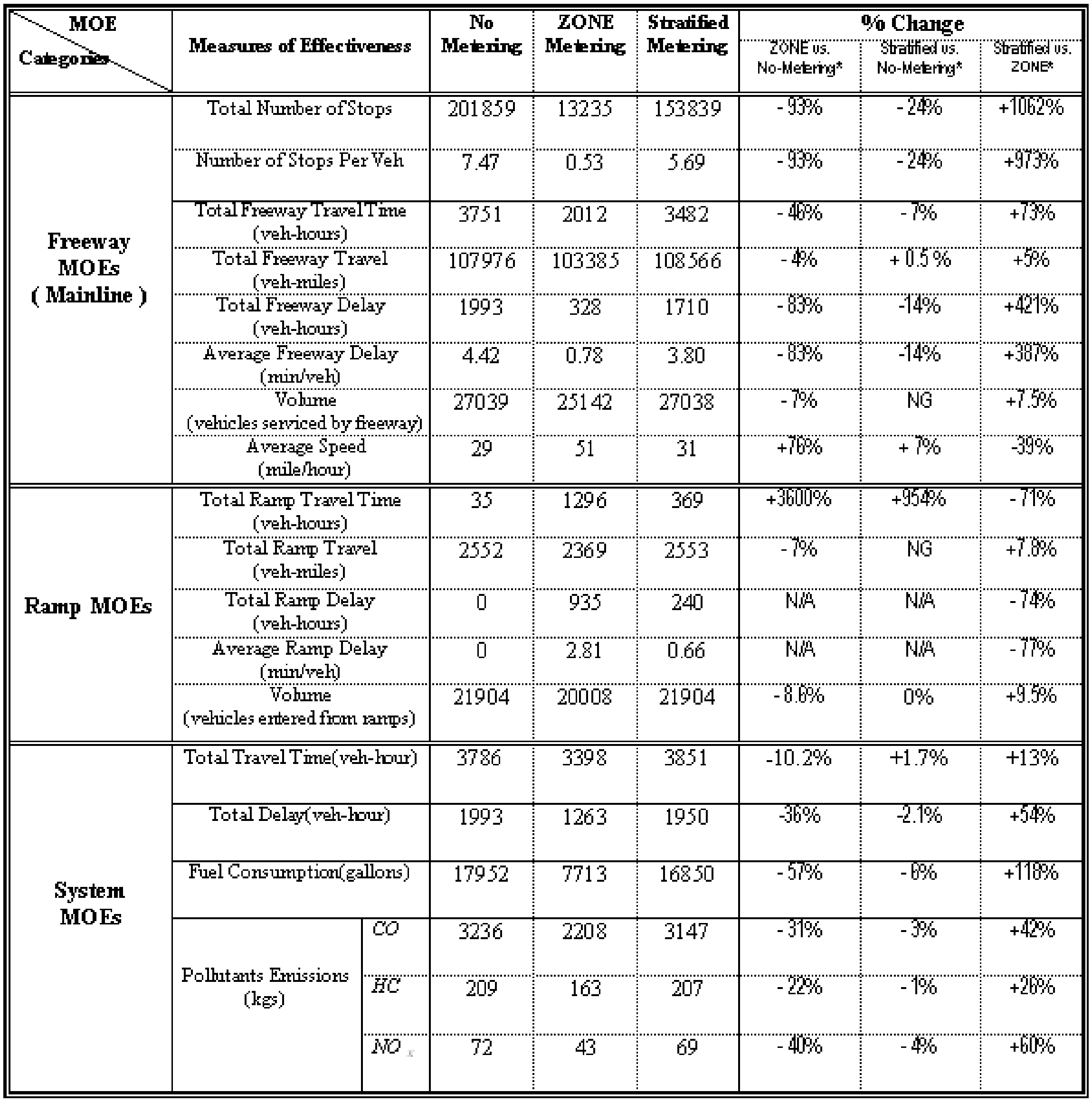
Figure 1.18 TH-169: Mainline Density Variation Nov 8th, 2000
Figure 1.19 TH-169: Mainline Density Variation Nov 13th, 2000
Figure 1.20 TH-169: Mainline Density Variation Nov 27th, 2000

Figure 1.21 I-94: Mainline Density Variation Oct 26th, 2000
Figure 1.22 I-94: Mainline Density Variation Nov 1st , 2000
Figure 1.23 I-94: Mainline Density Variation Nov 27th, 2000

MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		204477	72418	156880	-65%	-23%	+ 116%
	Number of Stops Per Veh		4.04	1.43	3.10	-65%	-23%	+ 116%
	Total Freeway Travel Time (veh-hours)		5587	4087	5314	-27%	-5%	+30%
	Total Freeway Travel (veh-miles)		196039	195940	196733	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		2150	912	1867	-58%	-13%	+104%
	Average Freeway Delay (min/veh)		2.55	1.08	2.21	-58%	-13%	+104%
	Volume (vehicles serviced by freeway)		50609	50610	50609	NG**	NG**	NG**
	Average Speed (mile/hour)		35.1	47.9	37.2	+37%	+6%	- 22%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		110	1506	452	+1269%	+310%	- 70%
	Total Ramp Travel (veh-miles)		4844	4901	4840	≈ 0%	0%	0%
	Total Ramp Delay (veh-hours)		0	1059	244	N/A***	N/A***	-77%
	Average Ramp Delay (min/veh)		0	1.549	0.357	N/A***	N/A***	-77%
	Volume (vehicles entered from ramps)		41000	41000	41000	NG***	NG***	NG***
System MOEs	Total Travel Time(veh-hour)		5697	5593	5766	-1.8%	+1.2%	+3.1%
	Total Delay(veh-hour)		2150	1971	2111	-8.3%	-1.8%	+7.1%
	Fuel Consumption(gallons)		22415	15322	21550	-32%	-4%	+40%
	Pollutants Emissions (kgs)	*CO*	4474	4033	4413	-10%	-1.4%	+ 9.4%
		HC	298	288	297	-3.3%	-0.3%	+3%
		NC_x	94	80.1	91	-15%	-3.2%	+13.6%

* Base case for the respective percentage change.
** Negligible since the presented results are for the entire congestion period.
*** No ramp congestion occurred under the no-metering scenario throughout this test site.

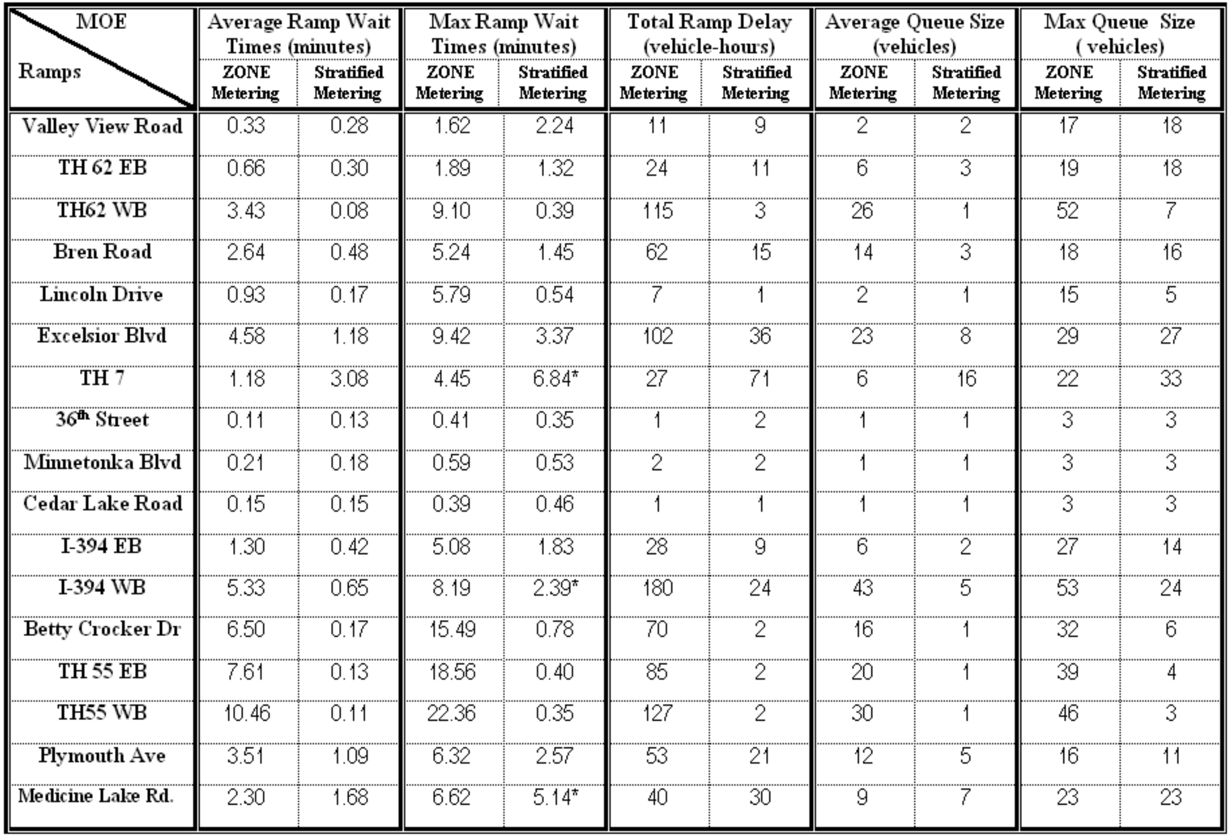
Table A.1 General Measures of Effectiveness: TH169NB Nov 8th, 2000, 14:00-20:00



MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		201859	13235	153839	- 93%	- 24%	+1062%
	Number of Stops Per Veh		7.47	0.53	5.69	- 93%	- 24%	+973%
	Total Freeway Travel Time (veh-hours)		3751	2012	3482	- 46%	- 7%	+73%
	Total Freeway Travel (veh-miles)		107976	103385	108566	- 4%	+ 0.5 %	+5%
	Total Freeway Delay (veh-hours)		1993	328	1710	- 83%	-14%	+421%
	Average Freeway Delay (min/veh)		4.42	0.78	3.80	- 83%	-14%	+387%
	Volume (vehicles serviced by freeway)		27039	25142	27038	- 7%	NG	+7.5%
	Average Speed (mile/hour)		29	51	31	+76%	+ 7%	-39%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		35	1296	369	+3600%	+954%	- 71%
	Total Ramp Travel (veh-miles)		2552	2369	2553	- 7%	NG	+7.8%
	Total Ramp Delay (veh-hours)		0	935	240	N/A	N/A	- 74%
	Average Ramp Delay (min/veh)		0	2.81	0.66	N/A	N/A	- 77%
	Volume (vehicles entered from ramps)		21904	20008	21904	- 8.6%	0%	+9.5%
System MOEs	Total Travel Time(veh-hour)		3786	3398	3851	-10.2%	+1.7%	+13%
	Total Delay(veh-hour)		1993	1263	1950	-36%	-2.1%	+54%
	Fuel Consumption(gallons)		17952	7713	16850	- 57%	- 6%	+118%
	Pollutants Emissions (kgs)	*CO*	3236	2208	3147	- 31%	- 3%	+42%
		HC	209	163	207	- 22%	- 1%	+26%
		NO $_x$	72	43	69	- 40%	- 4%	+60%

* Base case for the respective percentage change.

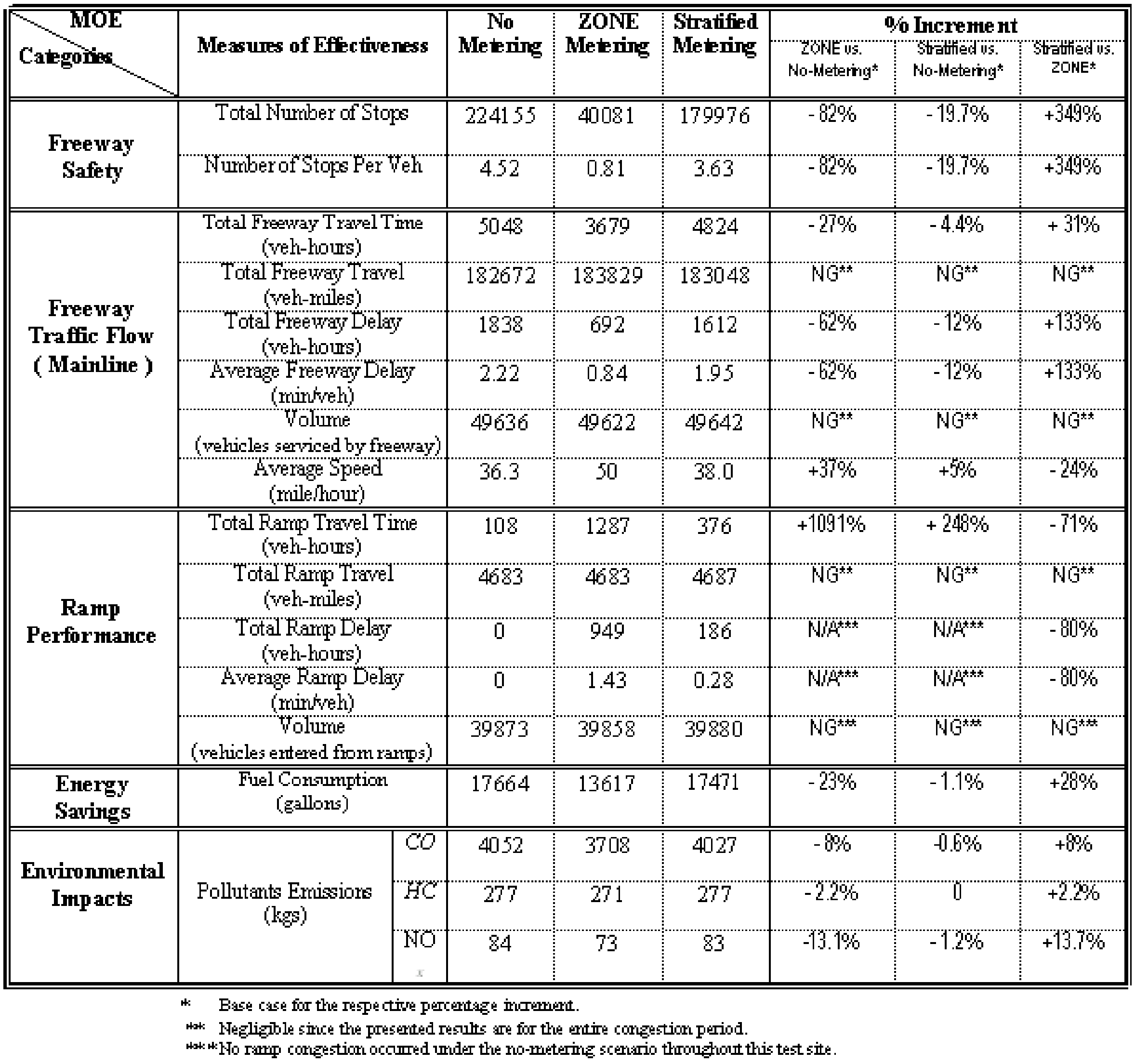
Table A.2 General Measures of Effectiveness: TH169NB Nov 8th, 2000, 15:00-18:00



MOE / Ramps	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering
Valley View Road	0.33	0.28	1.62	2.24	11	9	2	2	17	18
TH 62 EB	0.66	0.30	1.89	1.32	24	11	6	3	19	18
TH62 WB	3.43	0.08	9.10	0.39	115	3	26	1	52	7
Bren Road	2.64	0.48	5.24	1.45	62	15	14	3	18	16
Lincoln Drive	0.93	0.17	5.79	0.54	7	1	2	1	15	5
Excelsior Blvd	4.58	1.18	9.42	3.37	102	36	23	8	29	27
TH 7	1.18	3.08	4.45	6.84*	27	71	6	16	22	33
36th Street	0.11	0.13	0.41	0.35	1	2	1	1	3	3
Minnetonka Blvd	0.21	0.18	0.59	0.53	2	2	1	1	3	3
Cedar Lake Road	0.15	0.15	0.39	0.46	1	1	1	1	3	3
I-394 EB	1.30	0.42	5.08	1.83	28	9	6	2	27	14
I-394 WB	5.33	0.65	8.19	2.39*	180	24	43	5	53	24
Betty Crocker Dr	6.50	0.17	15.49	0.78	70	2	16	1	32	6
TH 55 EB	7.61	0.13	18.56	0.40	85	2	20	1	39	4
TH55 WB	10.46	0.11	22.36	0.35	127	2	30	1	46	3
Plymouth Ave	3.51	1.09	6.32	2.57	53	21	12	5	16	11
Medicine Lake Rd.	2.30	1.68	6.62	5.14*	40	30	9	7	23	23

*The maximum allowed ramp wait time is violated.

Table A.3 Ramp Measures of Effectiveness: TH169NB Nov 8th, 2000, 15:00-18:00



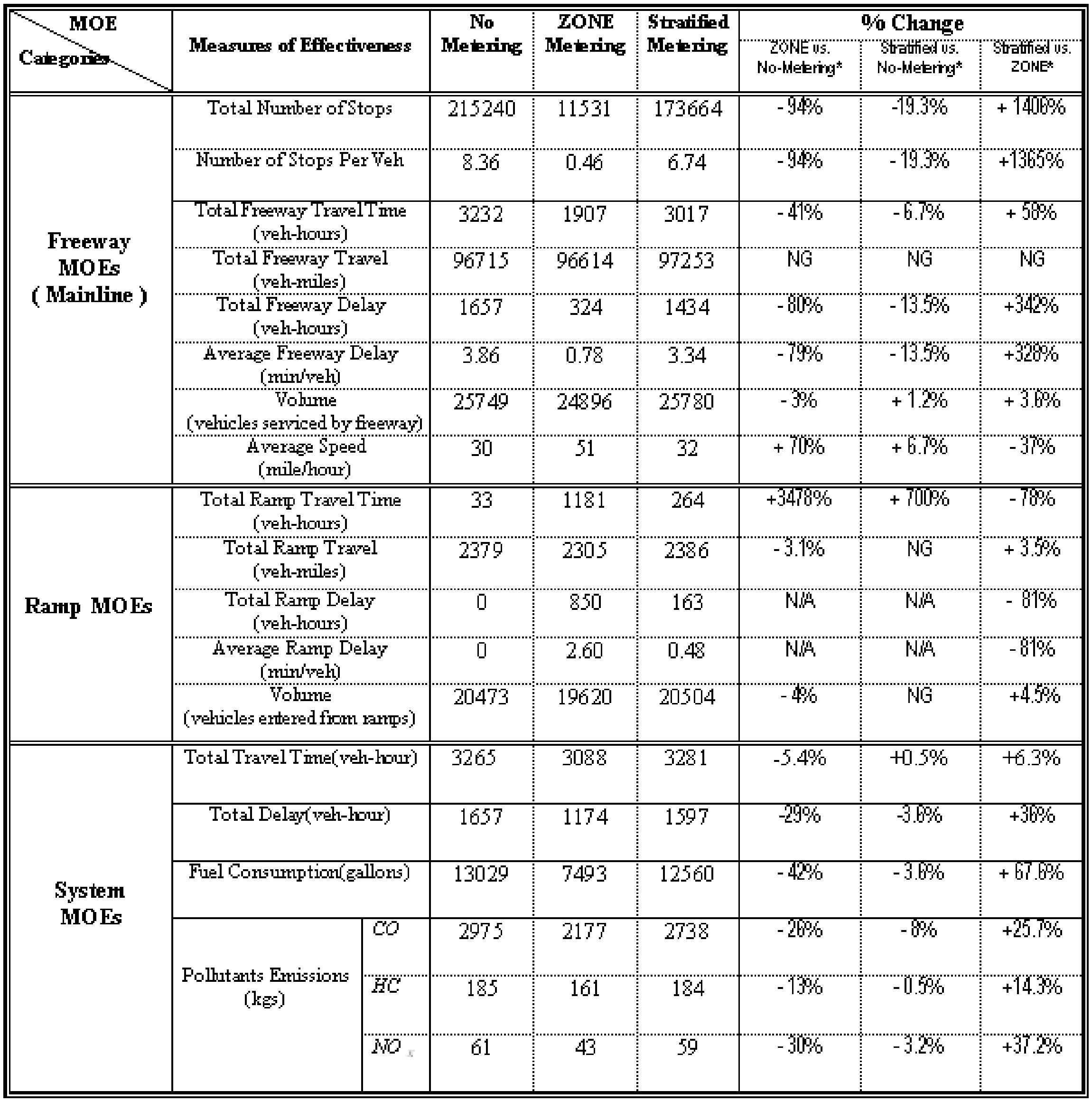
MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Increment: ZONE vs. No-Metering*	% Increment: Stratified vs. No-Metering*	% Increment: Stratified vs. ZONE*
Freeway Safety	Total Number of Stops		224155	40081	179976	- 82%	- 19.7%	+349%
	Number of Stops Per Veh		4.52	0.81	3.63	- 82%	- 19.7%	+349%
Freeway Traffic Flow (Mainline)	Total Freeway Travel Time (veh-hours)		5048	3679	4824	- 27%	- 4.4%	+ 31%
	Total Freeway Travel (veh-miles)		182672	183829	183048	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		1838	692	1612	- 62%	- 12%	+133%
	Average Freeway Delay (min/veh)		2.22	0.84	1.95	- 62%	- 12%	+133%
	Volume (vehicles serviced by freeway)		49636	49622	49642	NG**	NG**	NG**
	Average Speed (mile/hour)		36.3	50	38.0	+37%	+5%	- 24%
Ramp Performance	Total Ramp Travel Time (veh-hours)		108	1287	376	+1091%	+ 248%	- 71%
	Total Ramp Travel (veh-miles)		4683	4683	4687	NG**	NG**	NG**
	Total Ramp Delay (veh-hours)		0	949	186	N/A***	N/A***	- 80%
	Average Ramp Delay (min/veh)		0	1.43	0.28	N/A***	N/A***	- 80%
	Volume (vehicles entered from ramps)		39873	39858	39880	NG***	NG***	NG***
Energy Savings	Fuel Consumption (gallons)		17664	13617	17471	- 23%	- 1.1%	+28%
Environmental Impacts	Pollutants Emissions (kgs)	CO	4052	3708	4027	- 8%	-0.6%	+8%
		HC	277	271	277	- 2.2%	0	+2.2%
		NO	84	73	83	-13.1%	- 1.2%	+13.7%

* Base case for the respective percentage increment.

** Negligible since the presented results are for the entire congestion period.

***No ramp congestion occurred under the no-metering scenario throughout this test site.

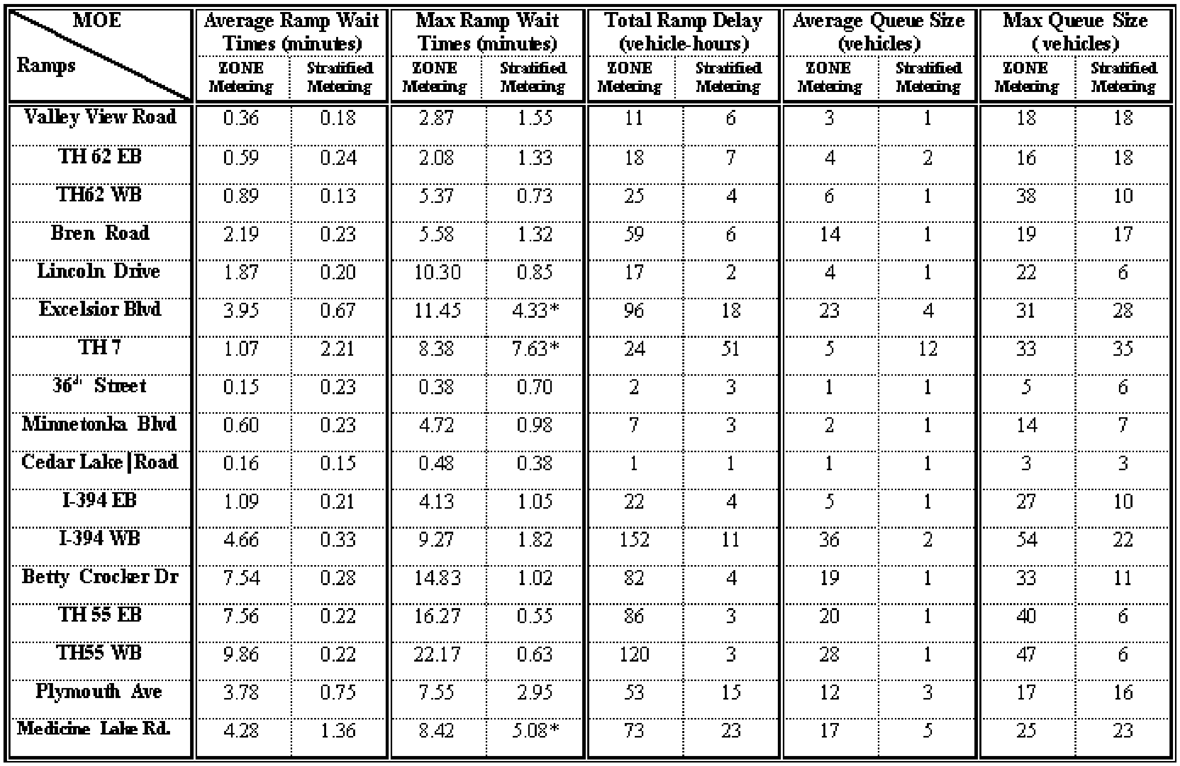
Table A.4 General Measures of Effectiveness: TH169NB Nov 13th, 2000, 14:00-20:00



MOE / Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		215240	11531	173664	- 94%	-19.3%	+ 1406%
	Number of Stops Per Veh		8.36	0.46	6.74	- 94%	- 19.3%	+1365%
	Total Freeway Travel Time (veh-hours)		3232	1907	3017	- 41%	- 6.7%	+ 58%
	Total Freeway Travel (veh-miles)		96715	96614	97253	NG	NG	NG
	Total Freeway Delay (veh-hours)		1657	324	1434	- 80%	- 13.5%	+342%
	Average Freeway Delay (min/veh)		3.86	0.78	3.34	- 79%	- 13.5%	+328%
	Volume (vehicles serviced by freeway)		25749	24896	25780	- 3%	+ 1.2%	+ 3.6%
	Average Speed (mile/hour)		30	51	32	+ 70%	+ 6.7%	- 37%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		33	1181	264	+3478%	+ 700%	- 78%
	Total Ramp Travel (veh-miles)		2379	2305	2386	- 3.1%	NG	+ 3.5%
	Total Ramp Delay (veh-hours)		0	850	163	N/A	N/A	- 81%
	Average Ramp Delay (min/veh)		0	2.60	0.48	N/A	N/A	- 81%
	Volume (vehicles entered from ramps)		20473	19620	20504	- 4%	NG	+4.5%
System MOEs	Total Travel Time(veh-hour)		3265	3088	3281	-5.4%	+0.5%	+6.3%
	Total Delay(veh-hour)		1657	1174	1597	-29%	-3.6%	+36%
	Fuel Consumption(gallons)		13029	7493	12560	- 42%	- 3.6%	+ 67.6%
	Pollutants Emissions (kgs)	*CO*	2975	2177	2738	- 26%	- 8%	+25.7%
		HC	185	161	184	- 13%	- 0.5%	+14.3%
		NO_x	61	43	59	- 30%	- 3.2%	+37.2%

* Base case for the respective percentage change.

Table A.5 General Measures of Effectiveness: TH169NB Nov 13th, 2000, 15:00-18:00



Ramps \ MOE	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering
Valley View Road	0.36	0.18	2.87	1.55	11	6	3	1	18	18
TH 62 EB	0.59	0.24	2.08	1.33	18	7	4	2	16	18
TH62 WB	0.89	0.13	5.37	0.73	25	4	6	1	38	10
Bren Road	2.19	0.23	5.58	1.32	59	6	14	1	19	17
Lincoln Drive	1.87	0.20	10.30	0.85	17	2	4	1	22	6
Excelsior Blvd	3.95	0.67	11.45	4.33*	96	18	23	4	31	28
TH 7	1.07	2.21	8.38	7.63*	24	51	5	12	33	35
36rd Street	0.15	0.23	0.38	0.70	2	3	1	1	5	6
Minnetonka Blvd	0.60	0.23	4.72	0.98	7	3	2	1	14	7
Cedar Lake Road	0.16	0.15	0.48	0.38	1	1	1	1	3	3
I-394 EB	1.09	0.21	4.13	1.05	22	4	5	1	27	10
I-394 WB	4.66	0.33	9.27	1.82	152	11	36	2	54	22
Betty Crocker Dr	7.54	0.28	14.83	1.02	82	4	19	1	33	11
TH 55 EB	7.56	0.22	16.27	0.55	86	3	20	1	40	6
TH55 WB	9.86	0.22	22.17	0.63	120	3	28	1	47	6
Plymouth Ave	3.78	0.75	7.55	2.95	53	15	12	3	17	16
Medicine Lake Rd.	4.28	1.36	8.42	5.08*	73	23	17	5	25	23

* The maximum allowed ramp wait time is violated.

Table A.6 Ramp Measures of Effectiveness : TH169NB Nov 13th, 2000, 15:00-18:00

MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		489129	127324	472581	- 74%	- 3%	+ 271%
	Number of Stops Per Veh		9.7	2.5	9.38	- 74%	- 3%	+275%
	Total Freeway Travel Time (veh-hours)		6816	4231	6803	- 38%	- 0.1%	+ 60%
	Total Freeway Travel (veh-miles)		184283	184728	184661	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		3829	1379	3806	- 64%	- 0.6%	+175%
	Average Freeway Delay (min/veh)		4.56	1.64	4.53	- 64%	- 0.6%	+175%
	Volume (vehicles serviced by freeway)		50350	50340	50346	NG**	NG**	NG**
	Average Speed (mile/hour)		27.03	44.3	27.14	+ 64%	+ 0.4%	- 38%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		137	1579	512	+ 1052%	+ 273%	- 68%
	Total Ramp Travel (veh-miles)		4887	4879	4886	NG**	NG**	NG**
	Total Ramp Delay (veh-hours)		18	1113	288	+6083%	+1500 %	- 74%
	Average Ramp Delay (min/veh)		0.03	1.61	0.42	+ 5266%	+1300%	- 74%
	Volume (vehicles entered from ramps)		41325	41320	41347	NG***	NG***	NG***
System MOEs	Total Travel Time(veh-hour)		6953	5810	7315	-16.4%	+5%	+25%
	Total Delay(veh-hour)		3847	2492	4094	-35%	+6.4%	+64%
	Fuel Consumption(gallons)		27232	18434	28060	- 32.3%	+3%	+ 52%
	Pollutants Emissions (kgs)	*CO*	5625	4642	5670	- 17.5%	+0.8%	+22%
		HC	375	332	377	- 11.5%	+0.5%	+14%
		NO_x	125	97	127	- 22%	+1.6%	+31%

* Base case for the respective percentage change.
** Negligible since the presented results are for the entire congestion period.
*** No ramp congestion occurred under the no-metering scenario throughout this test site.

Table A.7 General Measures of Effectiveness: TH169NB Nov 27th, 2000, 14:00-20:00

MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		462752	32264	460141	- 93%	- 0.5%	+1326%
	Number of Stops Per Veh		17.14	1.23	17.04	- 93%	- 0.5%	+1285%
	Total Freeway Travel Time (veh-hours)		4956	2061	4881	-58%	-1.5%	137%
	Total Freeway Travel (veh-miles)		98002	98655	98709	NG	NG	NG
	Total Freeway Delay (veh-hours)		3443	540	3416	- 84%	NG	+532%
	Average Freeway Delay (min/veh)		7.649	1.24	7.591	- 84%	NG	+512%
	Volume (vehicles serviced by freeway)		27004	26134	26998	- 3.2%	NG	+3.3%
	Average Speed (mile/hour)		19.7	48	20.2	+144%	+ 2.5%	- 58%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		61	1448	423	+ 2273%	+593%	- 71%
	Total Ramp Travel (veh-miles)		2596	2524	2601	-2.7%	NG	+3%
	Total Ramp Delay (veh-hours)		18	1045	279	+5705%	+1450%	- 73%
	Average Ramp Delay (min/veh)		0.049	2.95	0.755	+5920%	+1440%	- 74%
	Volume (vehicles entered from ramps)		22159	21293	22172	- 3.9%	NG	+4%
System MOEs	Total Travel Time(veh-hour)		5017	3509	5304	-30%	+5.7%	+51%
	Total Delay(veh-hour)		3461	1585	3695	+54%	+6.7%	+133%
	Fuel Consumption(gallons)		21090	9791	23948	- 53.5%	+ 13%	+144%
	Pollutants Emissions (kgs)	*CO*	4242	2738	4353	- 35%	+2.6%	+59%
		HC	274	199	280	- 27%	+2.1%	+40%
		NO_x	98	58	101	- 40%	+3.1%	+74%

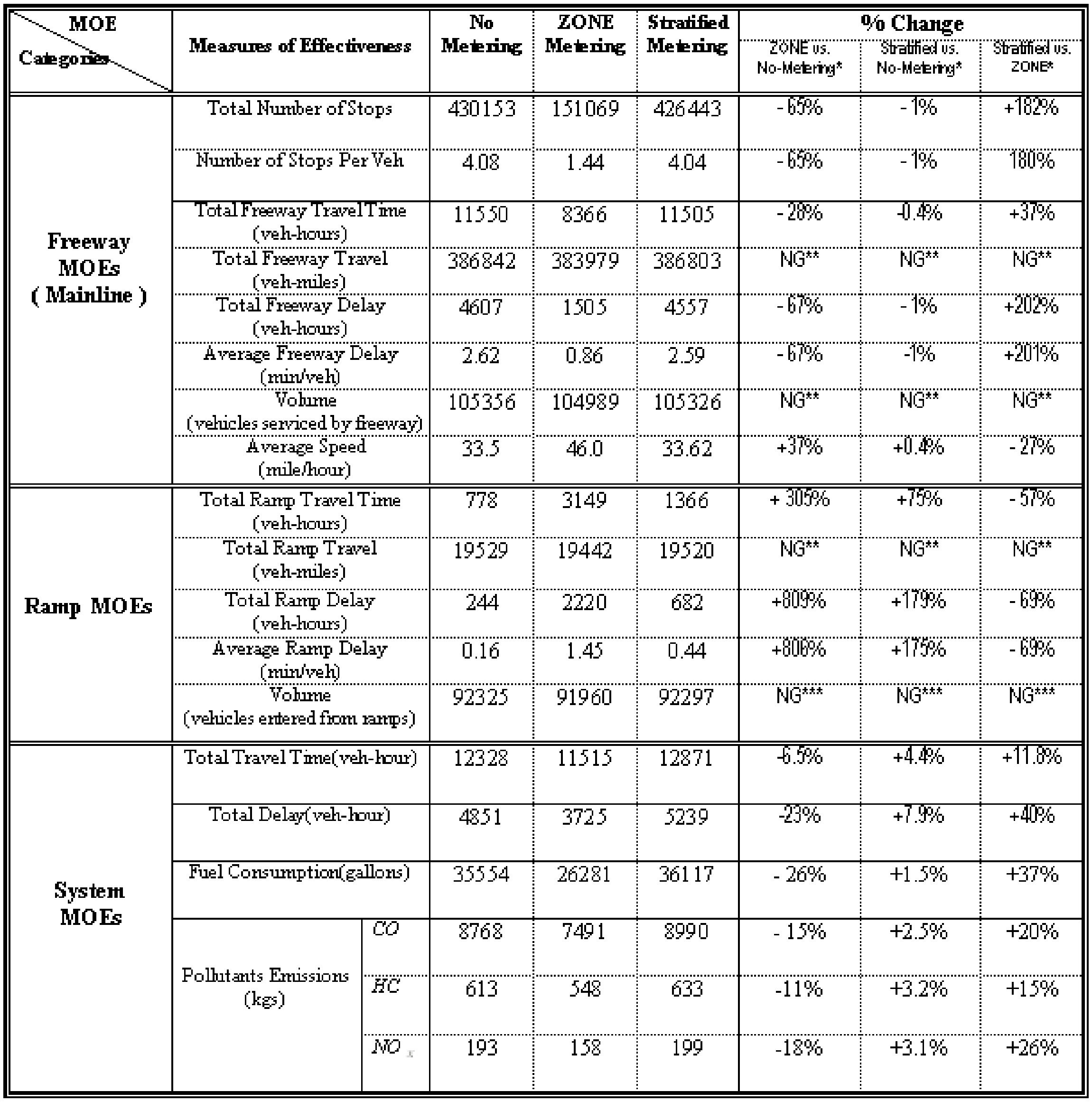
* Base case for the respective percentage change.

Table A.8 General Measures of Effectiveness: TH169NB Nov 27th, 2000, 15:00-18:00

MOE / Ramps	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering	ZONE Metering	Stratified Metering
Valley View Road	0.19	0.89	1.08	2.36	6	30	1	7	10	18
TH 62 EB	0.98	0.49	2.05	1.25	32	16	8	4	19	19
TH62 WB	4.73	0.21	10.07	0.58	155	7	34	2	53	12
Bren Road	2.37	0.57	5.50	1.27	63	18	14	4	18	16
Lincoln Drive	3.16	0.30	14.42	1.62	27	3	6	2	28	9
Excelsior Blvd	4.31	1.03	10.51	3.25	104	30	23	7	29	27
TH 7	2.39	2.24	7.12	5.73*	58	54	13	12	33	32
36th Street	0.22	0.28	0.92	0.56	3	4	2	2	6	5
Minnetonka Blvd	0.90	0.25	3.33	0.61	11	3	3	1	14	5
Cedar Lake Road	0.27	0.21	0.90	0.56	2	1	1	1	4	3
I-394 EB	1.76	0.99	4.39	3.46*	40	23	9	5	28	27
I-394 WB	3.86	0.85	6.84	2.89*	140	31	33	7	48	34
Betty Crocker Dr	5.07	0.43	13.90	2.07	71	6	16	2	30	19
TH 55 EB	8.63	0.28	19.09	0.77	117	4	27	2	41	8
TH55 WB	7.28	0.22	19.33	0.45	110	3	24	2	40	5
Plymouth Ave	2.99	0.85	6.72	1.77	51	17	12	4	16	14
Medicine Lake Rd.	3.14	1.63	12.26	4.29*	54	28	12	6	27	19

*The maximum allowed ramp wait time is violated.

Table A.9 Ramp Measures of Effectiveness : TH169NB Nov 27th, 2000, 15:00-18:00



MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		430153	151069	426443	- 65%	- 1%	+182%
	Number of Stops Per Veh		4.08	1.44	4.04	- 65%	- 1%	180%
	Total Freeway Travel Time (veh-hours)		11550	8366	11505	- 28%	-0.4%	+37%
	Total Freeway Travel (veh-miles)		386842	383979	386803	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		4607	1505	4557	- 67%	- 1%	+202%
	Average Freeway Delay (min/veh)		2.62	0.86	2.59	- 67%	-1%	+201%
	Volume (vehicles serviced by freeway)		105356	104989	105326	NG**	NG**	NG**
	Average Speed (mile/hour)		33.5	46.0	33.62	+37%	+0.4%	- 27%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		778	3149	1366	+ 305%	+75%	- 57%
	Total Ramp Travel (veh-miles)		19529	19442	19520	NG**	NG**	NG**
	Total Ramp Delay (veh-hours)		244	2220	682	+809%	+179%	- 69%
	Average Ramp Delay (min/veh)		0.16	1.45	0.44	+806%	+175%	- 69%
	Volume (vehicles entered from ramps)		92325	91960	92297	NG***	NG***	NG***
System MOEs	Total Travel Time(veh-hour)		12328	11515	12871	-6.5%	+4.4%	+11.8%
	Total Delay(veh-hour)		4851	3725	5239	-23%	+7.9%	+40%
	Fuel Consumption(gallons)		35554	26281	36117	- 26%	+1.5%	+37%
	Pollutants Emissions (kgs)	*CO*	8768	7491	8990	- 15%	+2.5%	+20%
		HC	613	548	633	-11%	+3.2%	+15%
		NO_x	193	158	199	-18%	+3.1%	+26%

* Base case for the respective percentage change.

** Negligible since the presented results are for the entire congestion period.

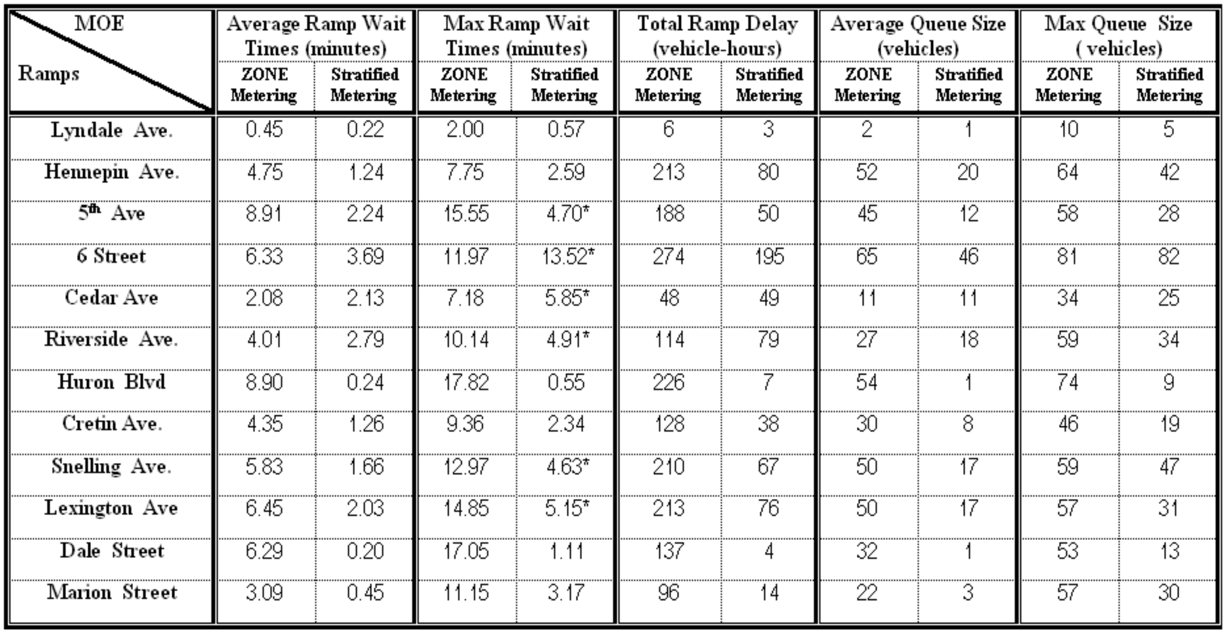
*** No ramp congestion occurred under the no-metering scenario throughout this test site.

Table A.10 General Measures of Effectiveness: I94EB Oct 26th, 2000, 14:00-20:00

MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		402058	106794	395354	- 73%	-2%	+270%
	Number of Stops Per Veh		7.32	3.25	7.20	- 55%	-2%	+121%
	Total Freeway Travel Time (veh-hours)		7510	4000	7427	- 47%	- 1%	+85%
	Total Freeway Travel (veh-miles)		207859	197307	207668	-5%	NG	+5.2%
	Total Freeway Delay (veh-hours)		4242	968	4164	- 77%	-2%	+330%
	Average Freeway Delay (min/veh)		4.63	1.11	4.55	- 76%	-2%	+309%
	Volume (vehicles serviced by freeway)		54910	52300	54884	- 5%	≈0%	+5%
	Average Speed (mile/hour)		27.6	49	28.0	+ 77%	+1.5%	-43%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		534	2686	1115	+402%	+108%	-58%
	Total Ramp Travel (veh-miles)		10427	9829	10423	-6%	NG	+6%
	Total Ramp Delay (veh-hours)		238	1861	670	+681%	+181%	- 64%
	Average Ramp Delay (min/veh)		0.296	2.45	0.833	+727%	+181%	- 66%
	Volume (vehicles entered from ramps)		48261	45650	48235	-5%	NG	+5.6%
System MOEs	Total Travel Time(veh-hour)		8044	6686	8539	-16.9%	+6%	+27%
	Total Delay(veh-hour)		4480	2829	4834	-37%	+7.9%	+70%
	Fuel Consumption(gallons)		27012	15533	27347	- 42%	+1.2%	+76%
	Pollutants Emissions (kgs)	*CO*	6553	4516	6785	-31%	+3.5%	+50%
		HC	458	335	477	-27%	+4%	+42%
		NO_x	151	97	155	- 35%	+2.6%	+59

* Base case for the respective percentage change.

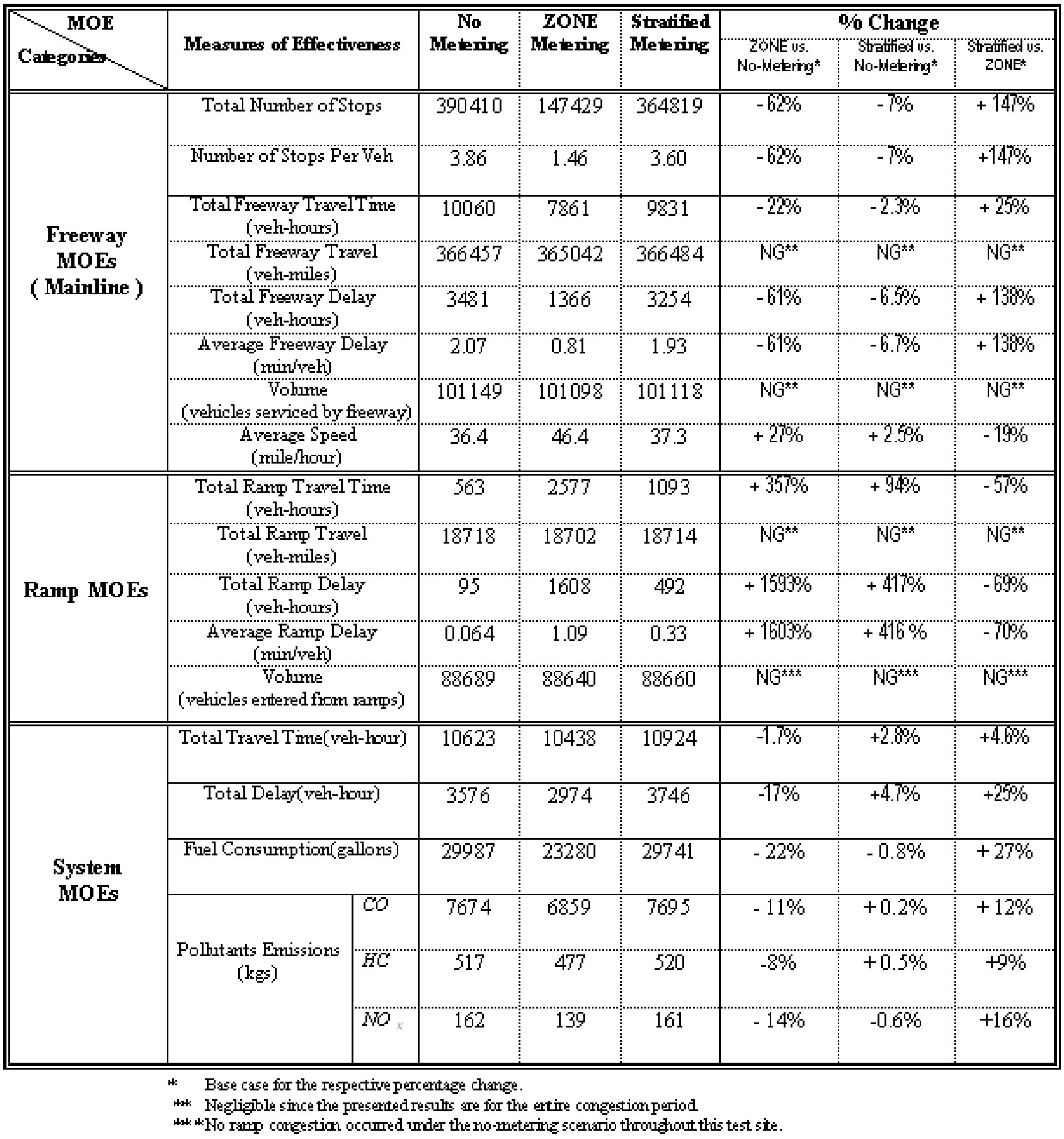
Table A.11 General Measures of Effectiveness: I94EB Oct 26th, 2000, 15:00-18:00



MOE / Ramps	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**
Lyndale Ave.	0.45	0.22	2.00	0.57	6	3	2	1	10	5
Hennepin Ave.	4.75	1.24	7.75	2.59	213	80	52	20	64	42
5th Ave	8.91	2.24	15.55	4.70*	188	50	45	12	58	28
6 Street	6.33	3.69	11.97	13.52*	274	195	65	46	81	82
Cedar Ave	2.08	2.13	7.18	5.85*	48	49	11	11	34	25
Riverside Ave.	4.01	2.79	10.14	4.91*	114	79	27	18	59	34
Huron Blvd	8.90	0.24	17.82	0.55	226	7	54	1	74	9
Cretin Ave.	4.35	1.26	9.36	2.34	128	38	30	8	46	19
Snelling Ave.	5.83	1.66	12.97	4.63*	210	67	50	17	59	47
Lexington Ave	6.45	2.03	14.85	5.15*	213	76	50	17	57	31
Dale Street	6.29	0.20	17.05	1.11	137	4	32	1	53	13
Marion Street	3.09	0.45	11.15	3.17	96	14	22	3	57	30

*The maximum allowed ramp wait time is violated.

Table A.12 Ramp Measures of Effectiveness : I94EB Oct 26th, 2000, 15:00-18:00



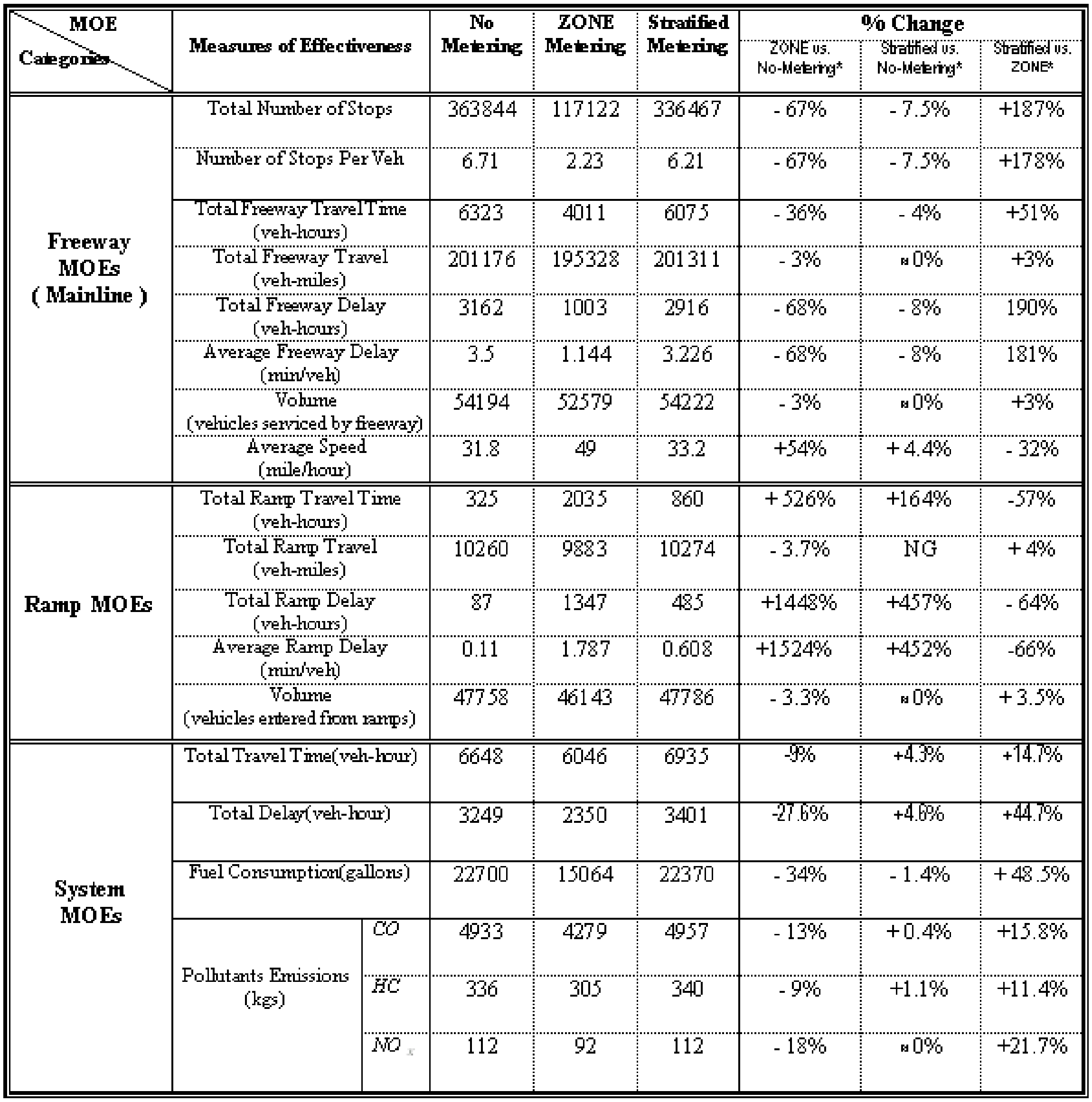
MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change ZONE vs. No-Metering*	% Change Stratified vs. No-Metering*	% Change Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		390410	147429	364819	- 62%	- 7%	+ 147%
	Number of Stops Per Veh		3.86	1.46	3.60	- 62%	- 7%	+147%
	Total Freeway Travel Time (veh-hours)		10060	7861	9831	- 22%	- 2.3%	+ 25%
	Total Freeway Travel (veh-miles)		366457	365042	366484	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		3481	1366	3254	- 61%	- 6.5%	+ 138%
	Average Freeway Delay (min/veh)		2.07	0.81	1.93	- 61%	- 6.7%	+ 138%
	Volume (vehicles serviced by freeway)		101149	101098	101118	NG**	NG**	NG**
	Average Speed (mile/hour)		36.4	46.4	37.3	+ 27%	+ 2.5%	- 19%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		563	2577	1093	+ 357%	+ 94%	- 57%
	Total Ramp Travel (veh-miles)		18718	18702	18714	NG**	NG**	NG**
	Total Ramp Delay (veh-hours)		95	1608	492	+ 1593%	+ 417%	- 69%
	Average Ramp Delay (min/veh)		0.064	1.09	0.33	+ 1603%	+ 416 %	- 70%
	Volume (vehicles entered from ramps)		88689	88640	88660	NG***	NG***	NG***
System MOEs	Total Travel Time(veh-hour)		10623	10438	10924	-1.7%	+2.8%	+4.6%
	Total Delay(veh-hour)		3576	2974	3746	-17%	+4.7%	+25%
	Fuel Consumption(gallons)		29987	23280	29741	- 22%	- 0.8%	+ 27%
	Pollutants Emissions (kgs)	*CO*	7674	6859	7695	- 11%	+ 0.2%	+ 12%
		HC	517	477	520	-8%	+ 0.5%	+9%
		NO $_x$	162	139	161	- 14%	-0.6%	+16%

* Base case for the respective percentage change.

** Negligible since the presented results are for the entire congestion period.

***No ramp congestion occurred under the no-metering scenario throughout this test site.

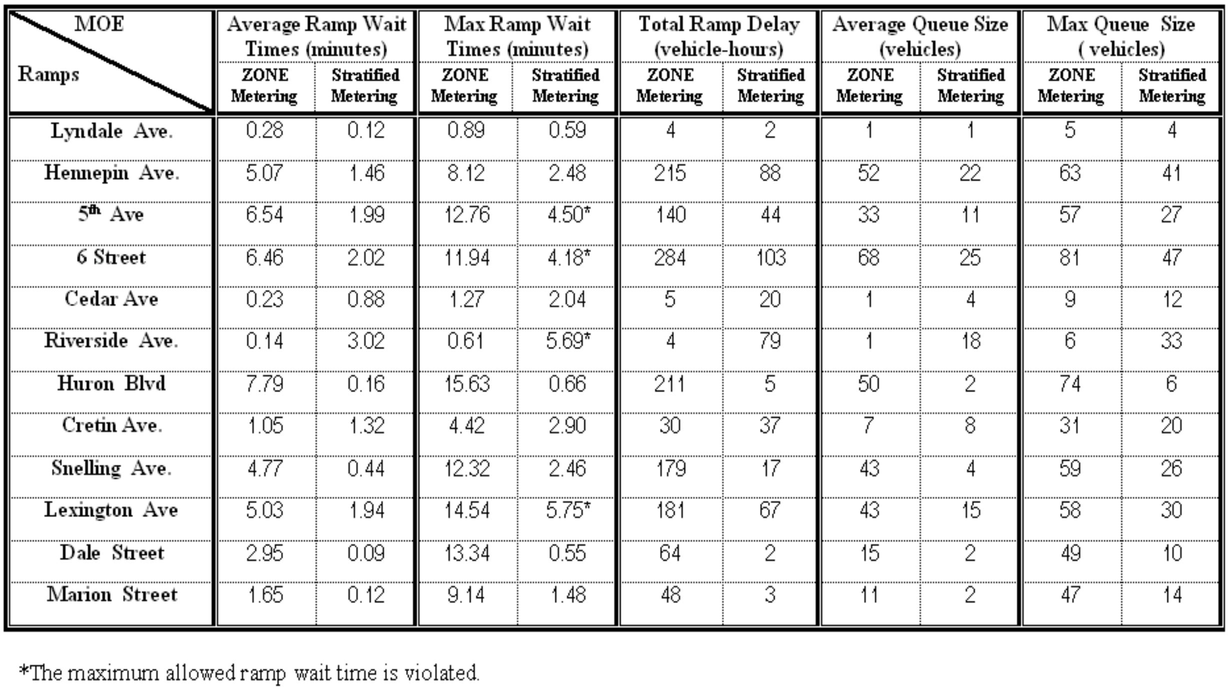
Table A.13 General Measures of Effectiveness: I94EB Nov 1st, 2000, 14:00-20:00



MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change ZONE vs. No-Metering*	% Change Stratified vs. No-Metering*	% Change Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		363844	117122	336467	- 67%	- 7.5%	+187%
	Number of Stops Per Veh		6.71	2.23	6.21	- 67%	- 7.5%	+178%
	Total Freeway Travel Time (veh-hours)		6323	4011	6075	- 36%	- 4%	+51%
	Total Freeway Travel (veh-miles)		201176	195328	201311	- 3%	≈ 0%	+3%
	Total Freeway Delay (veh-hours)		3162	1003	2916	- 68%	- 8%	190%
	Average Freeway Delay (min/veh)		3.5	1.144	3.226	- 68%	- 8%	181%
	Volume (vehicles serviced by freeway)		54194	52579	54222	- 3%	≈ 0%	+3%
	Average Speed (mile/hour)		31.8	49	33.2	+54%	+ 4.4%	- 32%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		325	2035	860	+ 526%	+164%	-57%
	Total Ramp Travel (veh-miles)		10260	9883	10274	- 3.7%	NG	+ 4%
	Total Ramp Delay (veh-hours)		87	1347	485	+1448%	+457%	- 64%
	Average Ramp Delay (min/veh)		0.11	1.787	0.608	+1524%	+452%	-66%
	Volume (vehicles entered from ramps)		47758	46143	47786	- 3.3%	≈ 0%	+ 3.5%
System MOEs	Total Travel Time(veh-hour)		6648	6046	6935	-9%	+4.3%	+14.7%
	Total Delay(veh-hour)		3249	2350	3401	-27.6%	+4.6%	+44.7%
	Fuel Consumption(gallons)		22700	15064	22370	- 34%	- 1.4%	+ 48.5%
	Pollutants Emissions (kgs)	*CO*	4933	4279	4957	- 13%	+ 0.4%	+15.8%
		HC	336	305	340	- 9%	+1.1%	+11.4%
		NO $_x$	112	92	112	- 18%	≈ 0%	+21.7%

*Base case for the respective percentage increment.

Table A.14 General Measures of Effectiveness: I94EB Nov 1st, 2000, 15:00-18:00



MOE / Ramps	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**
Lyndale Ave.	0.28	0.12	0.89	0.59	4	2	1	1	5	4
Hennepin Ave.	5.07	1.46	8.12	2.48	215	88	52	22	63	41
5th Ave	6.54	1.99	12.76	4.50*	140	44	33	11	57	27
6 Street	6.46	2.02	11.94	4.18*	284	103	68	25	81	47
Cedar Ave	0.23	0.88	1.27	2.04	5	20	1	4	9	12
Riverside Ave.	0.14	3.02	0.61	5.69*	4	79	1	18	6	33
Huron Blvd	7.79	0.16	15.63	0.66	211	5	50	2	74	6
Cretin Ave.	1.05	1.32	4.42	2.90	30	37	7	8	31	20
Snelling Ave.	4.77	0.44	12.32	2.46	179	17	43	4	59	26
Lexington Ave	5.03	1.94	14.54	5.75*	181	67	43	15	58	30
Dale Street	2.95	0.09	13.34	0.55	64	2	15	2	49	10
Marion Street	1.65	0.12	9.14	1.48	48	3	11	2	47	14

*The maximum allowed ramp wait time is violated.

Table A.15 Ramp Measures of Effectiveness : I94EB Nov 1st, 2000, 15:00-18:00

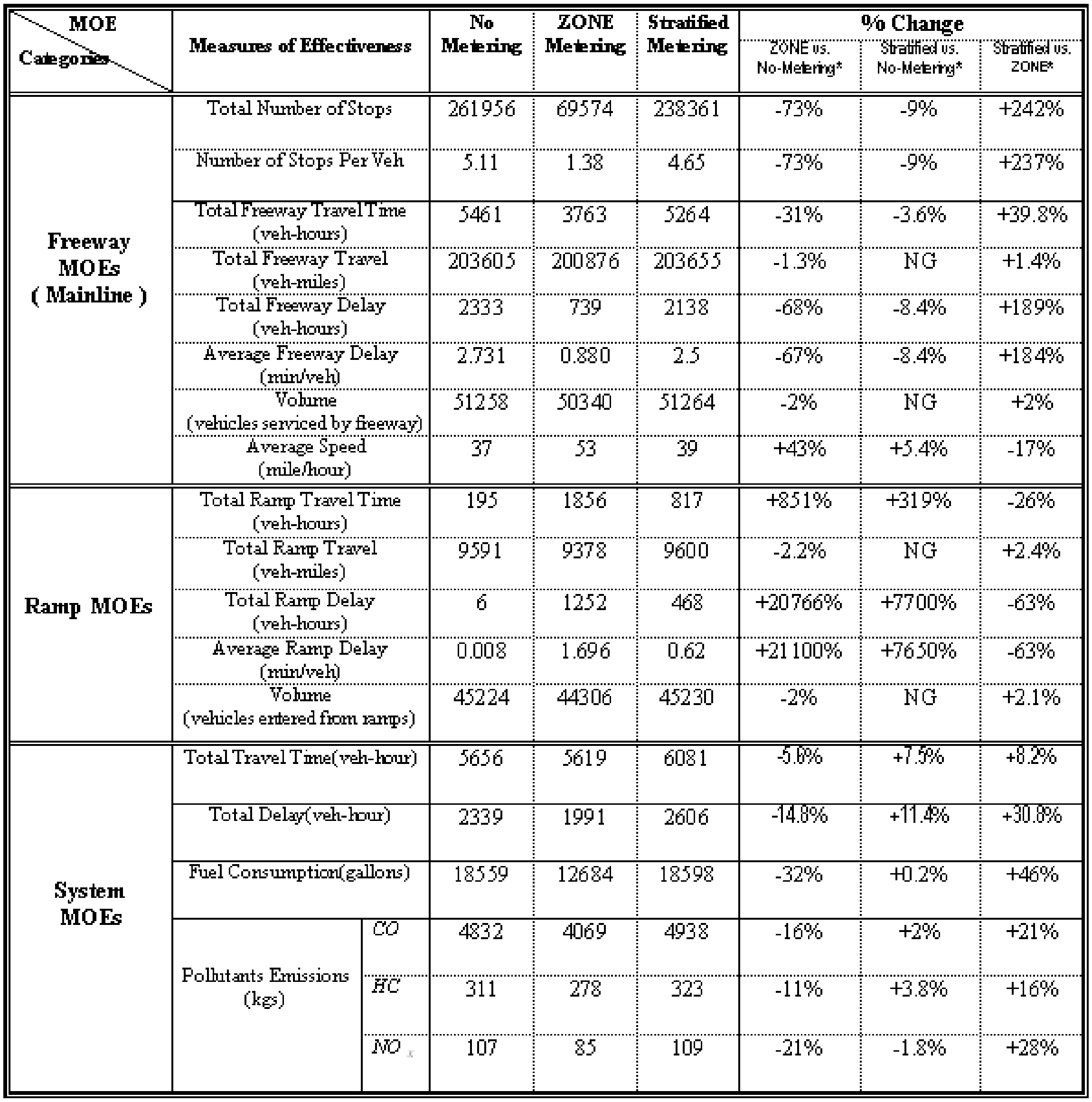
MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change ZONE vs. No-Metering*	% Change Stratified vs. No-Metering*	% Change Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		277024	87727	255940	-68%	-7.6%	+192%
	Number of Stops Per Veh		2.94	0.92	2.71	-68%	-7.8%	+194%
	Total Freeway Travel Time (veh-hours)		9026	7412	8875	-18%	-1.7%	+19.7%
	Total Freeway Travel (veh-miles)		365484	366569	366279	NG**	NG**	NG**
	Total Freeway Delay (veh-hours)		2546	979	2380	-62%	-6.5%	+143%
	Average Freeway Delay (min/veh)		1.62	0.62	1.51	-62%	-6.8%	+143%
	Volume (vehicles serviced by freeway)		94365	94365	94365	NG**	NG**	NG**
	Average Speed (mile/hour)		40.5	49.5	41.3	+22%	+2%	-16%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		400	2217	1021	+454%	+155%	-54%
	Total Ramp Travel (veh-miles)		17185	17185	17185	NG	NG	NG
	Total Ramp Delay (veh-hours)		7	1371	474	+19485%	+6671%	-65%
	Average Ramp Delay (min/veh)		NG	0.99	0.34	NA	NA	-66%
	Volume (vehicles entered from ramps)		82943	82943	82943	NG***	NG***	NG***
System MOEs	Total Travel Time(veh-hour)		9426	9629	9896	+2%	+4.9%	+2.8%
	Total Delay(veh-hour)		2553	2350	2854	-7.9%	+11%	+21%
	Fuel Consumption(gallons)		24501	19080	24809	-22%	+1.2%	+30%
	Pollutants Emissions (kgs)	*CO*	7013	6479	7163	-7.6%	+2.1%	+10%
		HC	445	427	459	-4%	+3.1%	+7.5%
		NO_x	144	128	146	-11%	+1.4%	+14%

* Base case for the respective percentage change.

** Negligible since the presented results are for the entire congestion period.

*** No ramp congestion occurred under the no-metering scenario throughout this test site.

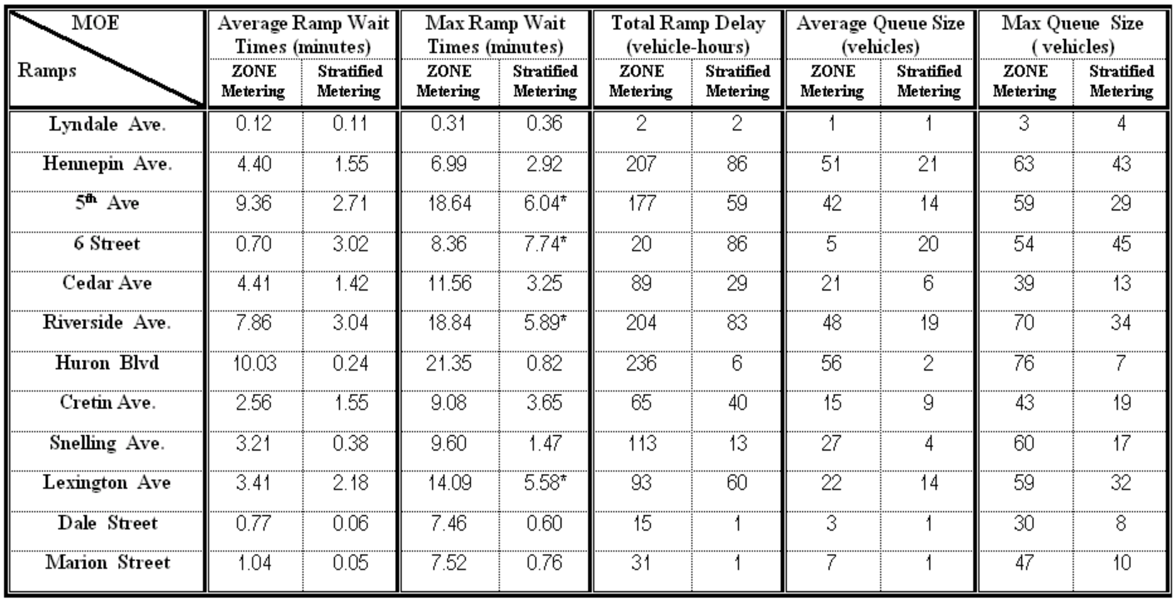
Table A.16 General Measures of Effectiveness: I94EB Nov 27th, 2000, 14:00-20:00



MOE Categories	Measures of Effectiveness		No Metering	ZONE Metering	Stratified Metering	% Change		
						ZONE vs. No-Metering*	Stratified vs. No-Metering*	Stratified vs. ZONE*
Freeway MOEs (Mainline)	Total Number of Stops		261956	69574	238361	-73%	-9%	+242%
	Number of Stops Per Veh		5.11	1.38	4.65	-73%	-9%	+237%
	Total Freeway Travel Time (veh-hours)		5461	3763	5264	-31%	-3.6%	+39.8%
	Total Freeway Travel (veh-miles)		203605	200876	203655	-1.3%	NG	+1.4%
	Total Freeway Delay (veh-hours)		2333	739	2138	-68%	-8.4%	+189%
	Average Freeway Delay (min/veh)		2.731	0.880	2.5	-67%	-8.4%	+184%
	Volume (vehicles serviced by freeway)		51258	50340	51264	-2%	NG	+2%
	Average Speed (mile/hour)		37	53	39	+43%	+5.4%	-17%
Ramp MOEs	Total Ramp Travel Time (veh-hours)		195	1856	817	+851%	+319%	-26%
	Total Ramp Travel (veh-miles)		9591	9378	9600	-2.2%	NG	+2.4%
	Total Ramp Delay (veh-hours)		6	1252	468	+20766%	+7700%	-63%
	Average Ramp Delay (min/veh)		0.008	1.696	0.62	+21100%	+7650%	-63%
	Volume (vehicles entered from ramps)		45224	44306	45230	-2%	NG	+2.1%
System MOEs	Total Travel Time(veh-hour)		5656	5619	6081	-5.0%	+7.5%	+8.2%
	Total Delay(veh-hour)		2339	1991	2606	-14.8%	+11.4%	+30.8%
	Fuel Consumption(gallons)		18559	12684	18598	-32%	+0.2%	+46%
	Pollutants Emissions (kgs)	*CO*	4832	4069	4938	-16%	+2%	+21%
		HC	311	278	323	-11%	+3.8%	+16%
		NO $_x$	107	85	109	-21%	-1.8%	+28%

* Base case for the respective percentage change.

Table A.17 General Measures of Effectiveness: I94EB Nov 27th, 2000, 15:00-18:00



MOE Ramps	Average Ramp Wait Times (minutes)		Max Ramp Wait Times (minutes)		Total Ramp Delay (vehicle-hours)		Average Queue Size (vehicles)		Max Queue Size (vehicles)	
	ZONE Metering	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**	**ZONE Metering**	**Stratified Metering**
Lyndale Ave.	0.12	0.11	0.31	0.36	2	2	1	1	3	4
Hennepin Ave.	4.40	1.55	6.99	2.92	207	86	51	21	63	43
5th Ave	9.36	2.71	18.64	6.04*	177	59	42	14	59	29
6 Street	0.70	3.02	8.36	7.74*	20	86	5	20	54	45
Cedar Ave	4.41	1.42	11.56	3.25	89	29	21	6	39	13
Riverside Ave.	7.86	3.04	18.84	5.89*	204	83	48	19	70	34
Huron Blvd	10.03	0.24	21.35	0.82	236	6	56	2	76	7
Cretin Ave.	2.56	1.55	9.08	3.65	65	40	15	9	43	19
Snelling Ave.	3.21	0.38	9.60	1.47	113	13	27	4	60	17
Lexington Ave	3.41	2.18	14.09	5.58*	93	60	22	14	59	32
Dale Street	0.77	0.06	7.46	0.60	15	1	3	1	30	8
Marion Street	1.04	0.05	7.52	0.76	31	1	7	1	47	10

*The maximum allowed ramp wait time is violated.

Table A.18 Ramp Measures of Effectiveness: I94EB Nov 27th, 2000, 15:00-18:00

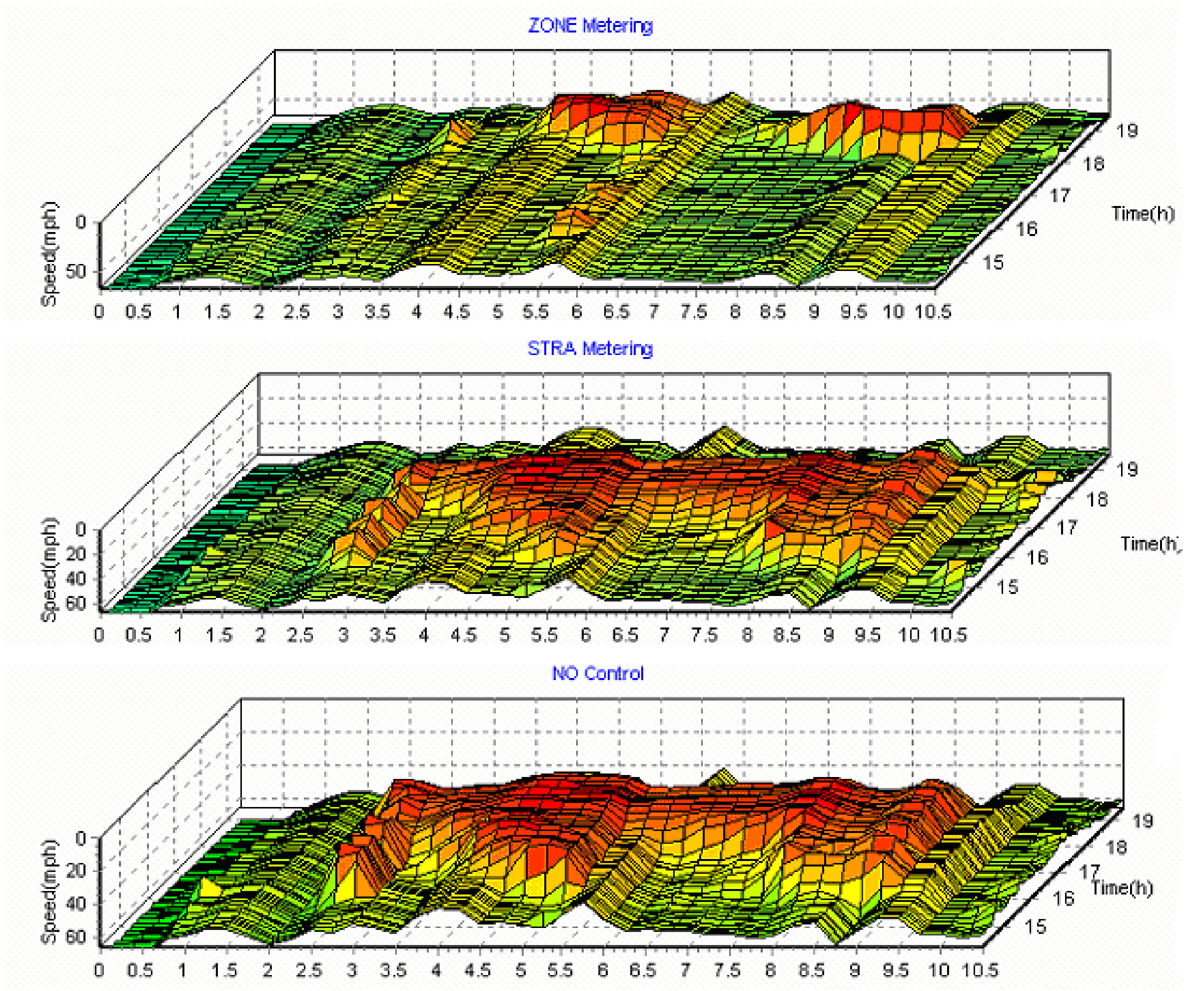


Figure A.19 TH169: Mainline Speed Variation Nov 8th, 2000

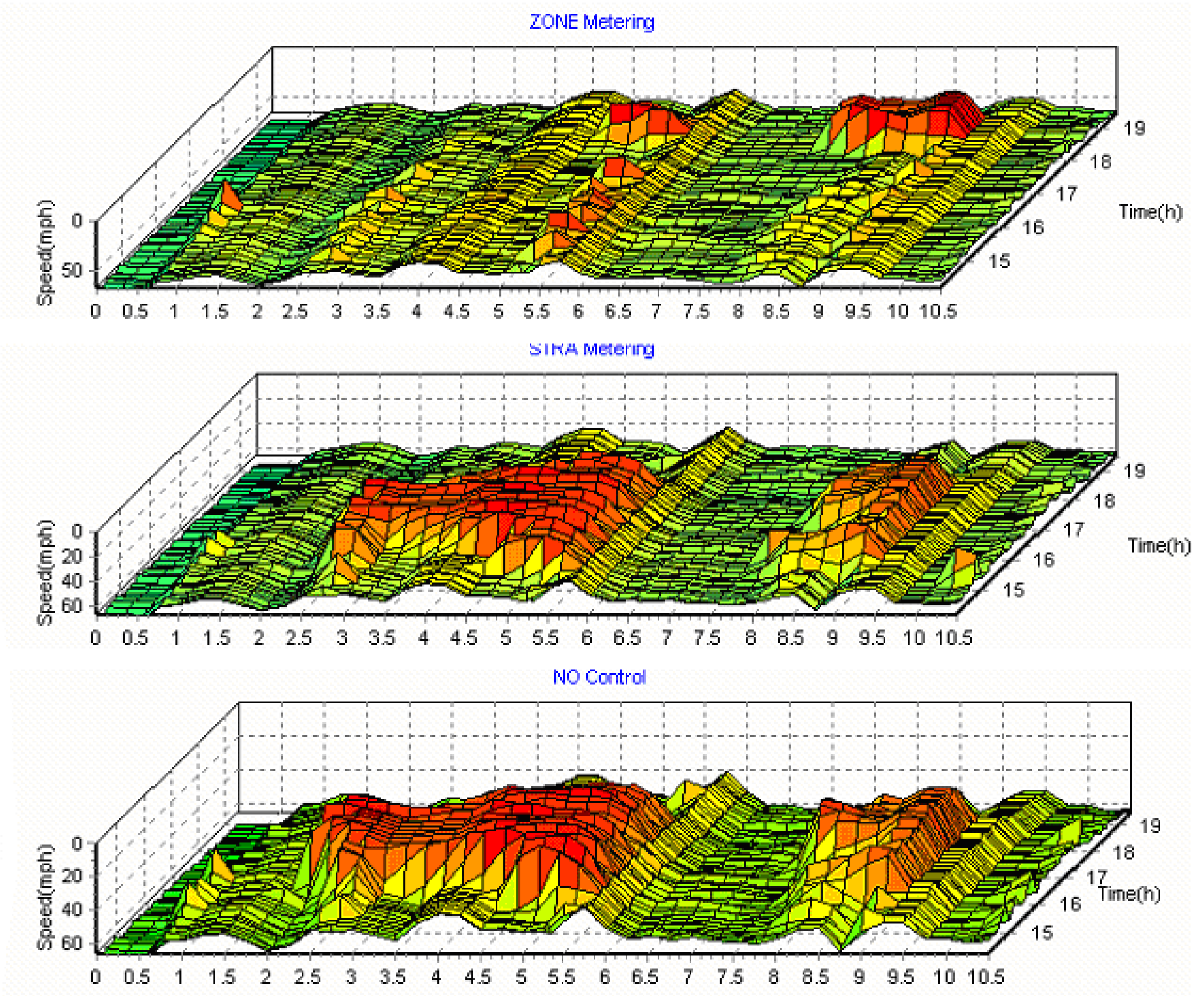


Figure A.20 TH169: Mainline Speed Variation Nov 13th, 2000

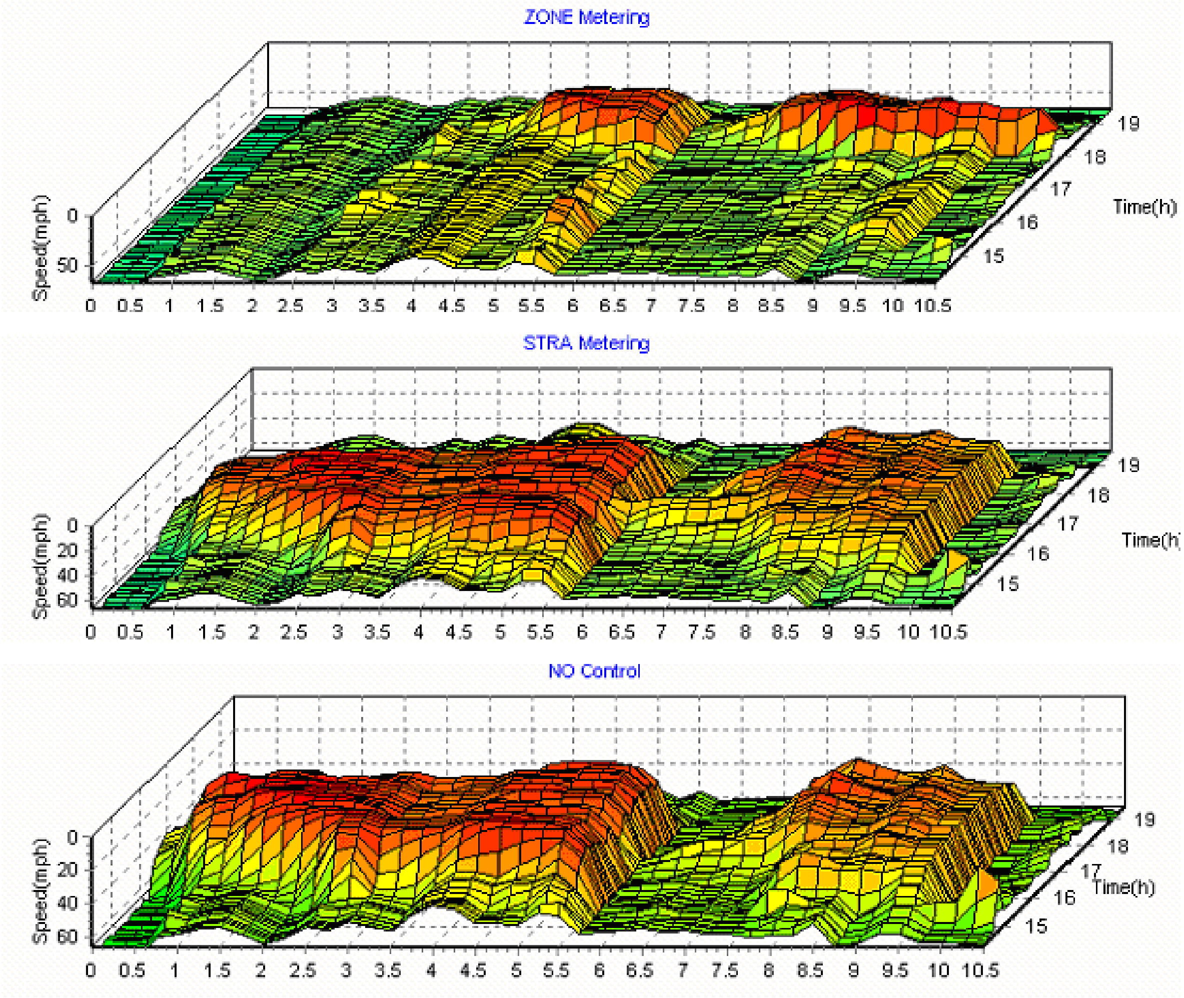


Figure A.21 TH169: Mainline Speed Variation Nov 27th, 2000

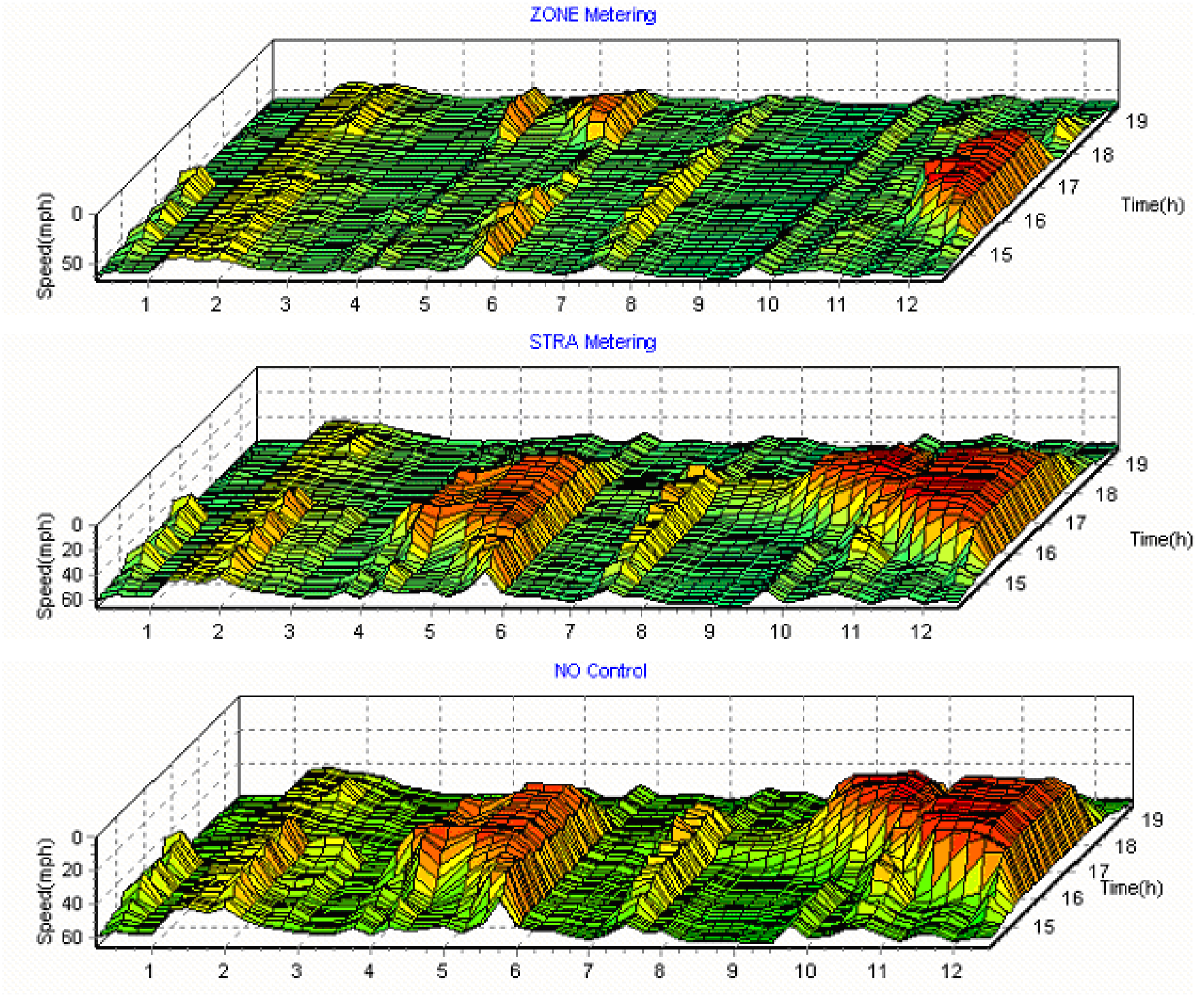


Figure A.22 I-94: Mainline Speed Variation Oct 26th, 2000

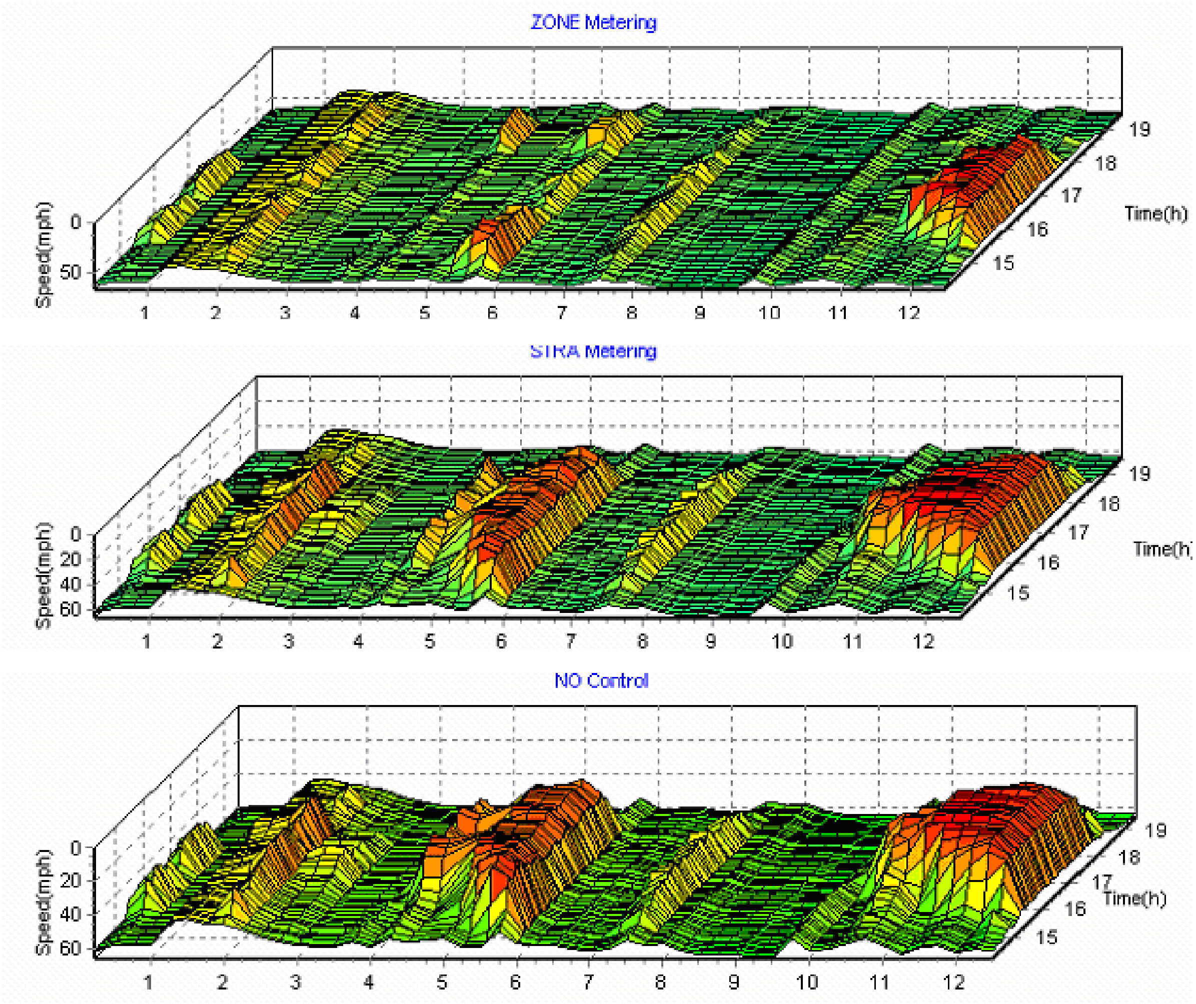


Figure A.23 I-94: Mainline Speed Variation Nov 1st, 2000

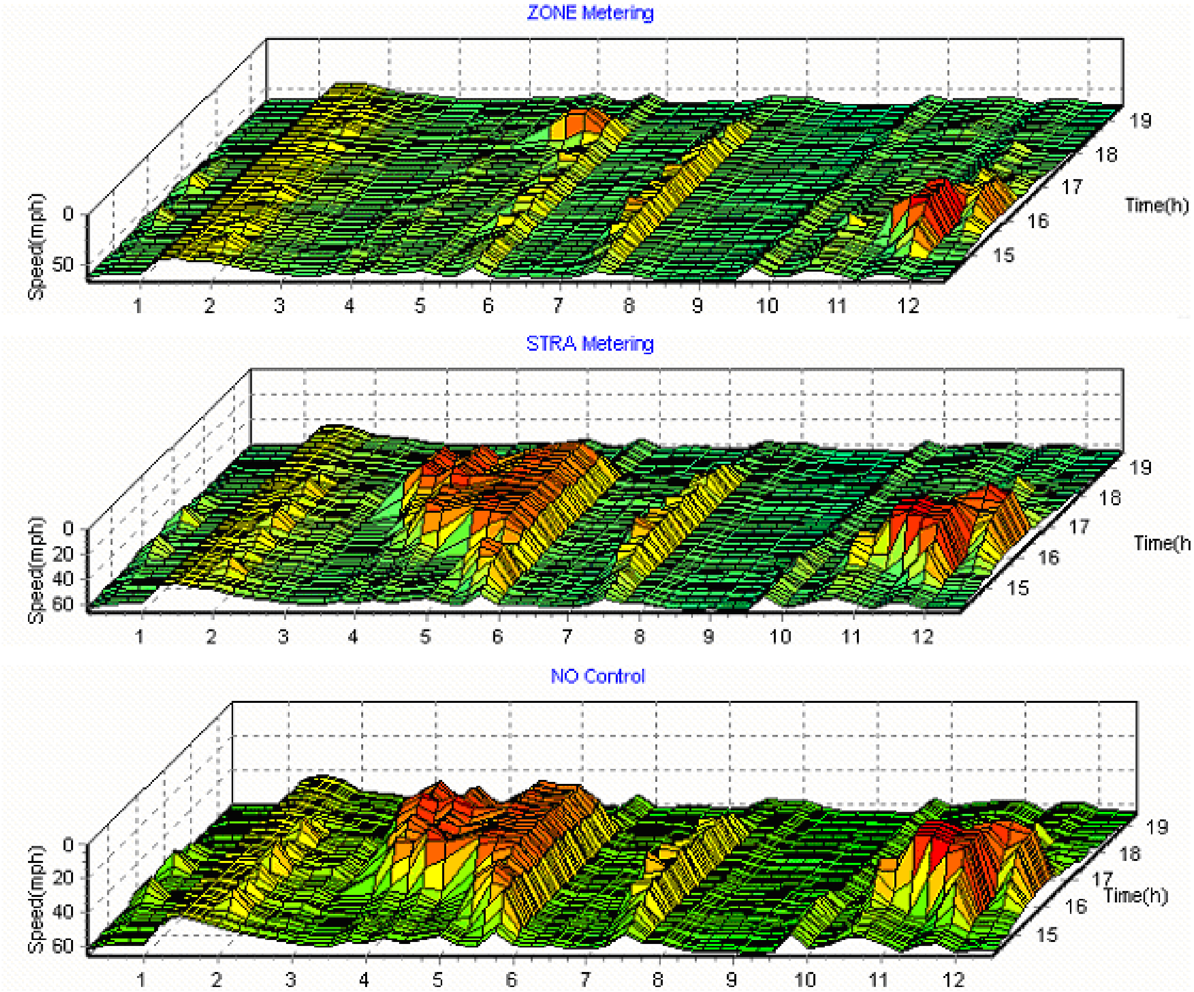


Figure A.24 I-94: Mainline Speed Variation Nov 27th, 2000

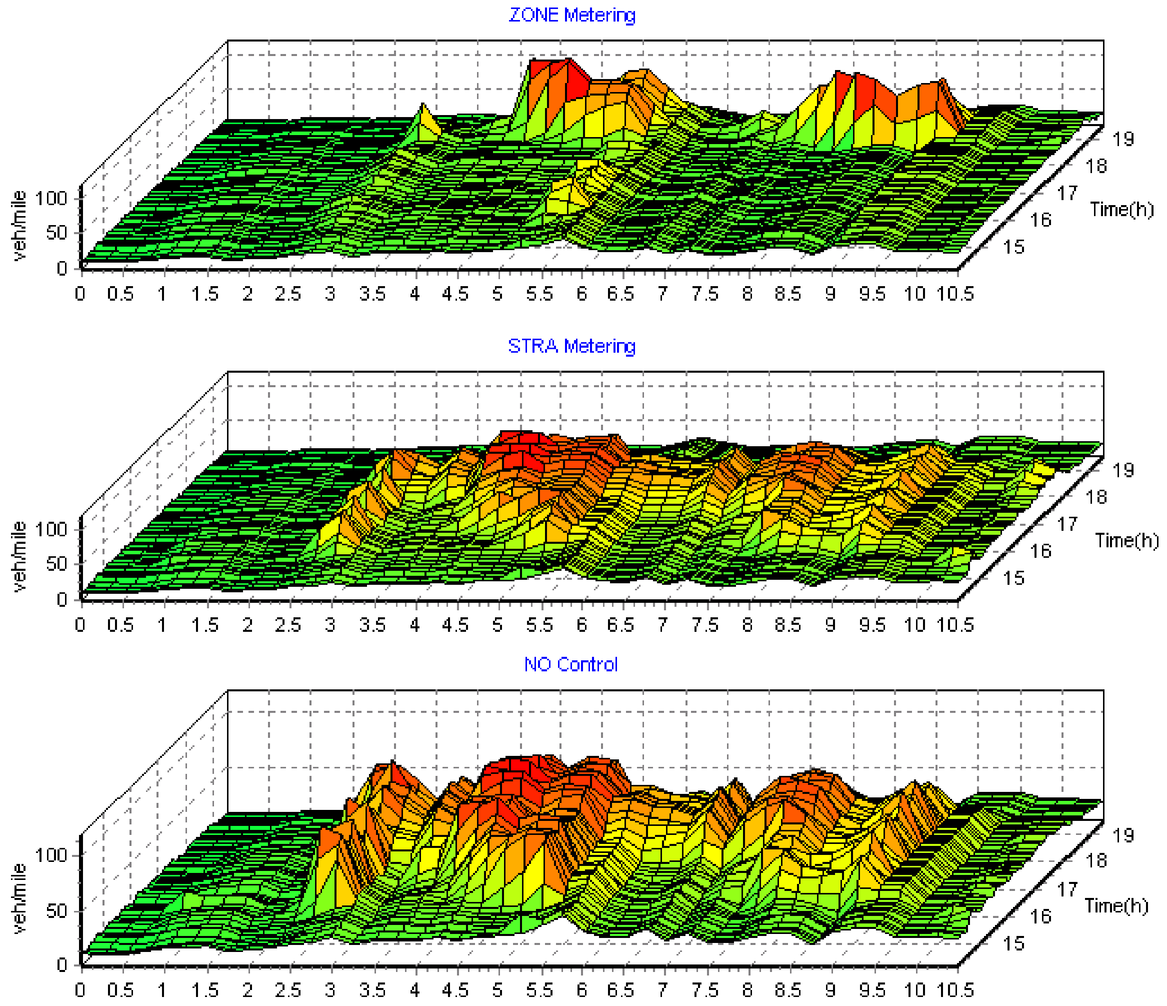
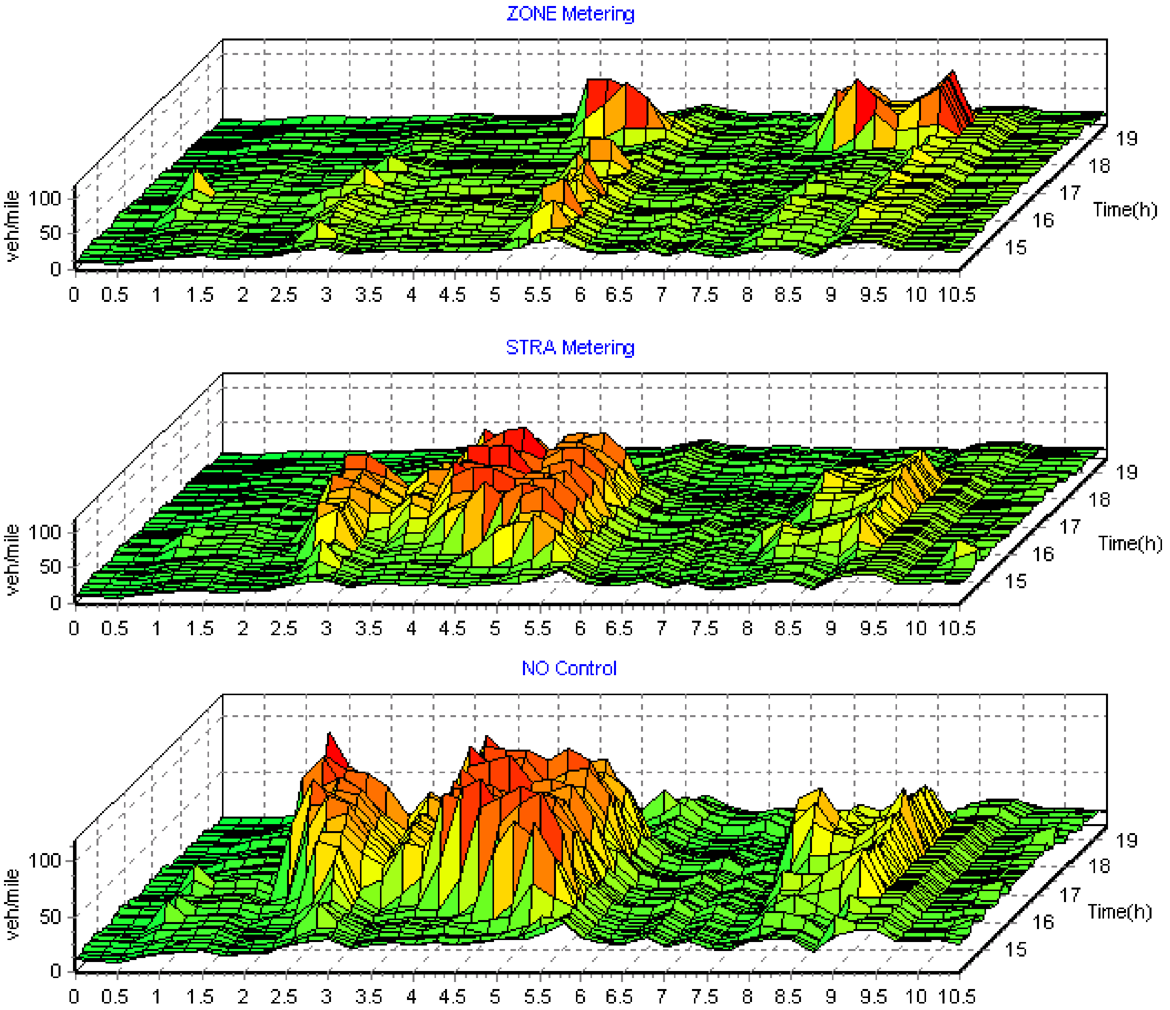


Figure A.25 TH169: Mainline Density Variation Nov 8th, 2000


ZONE Metering

STRA Metering

NO Control

Figure A.26 TH169: Mainline Density Variation Nov 13th, 2000

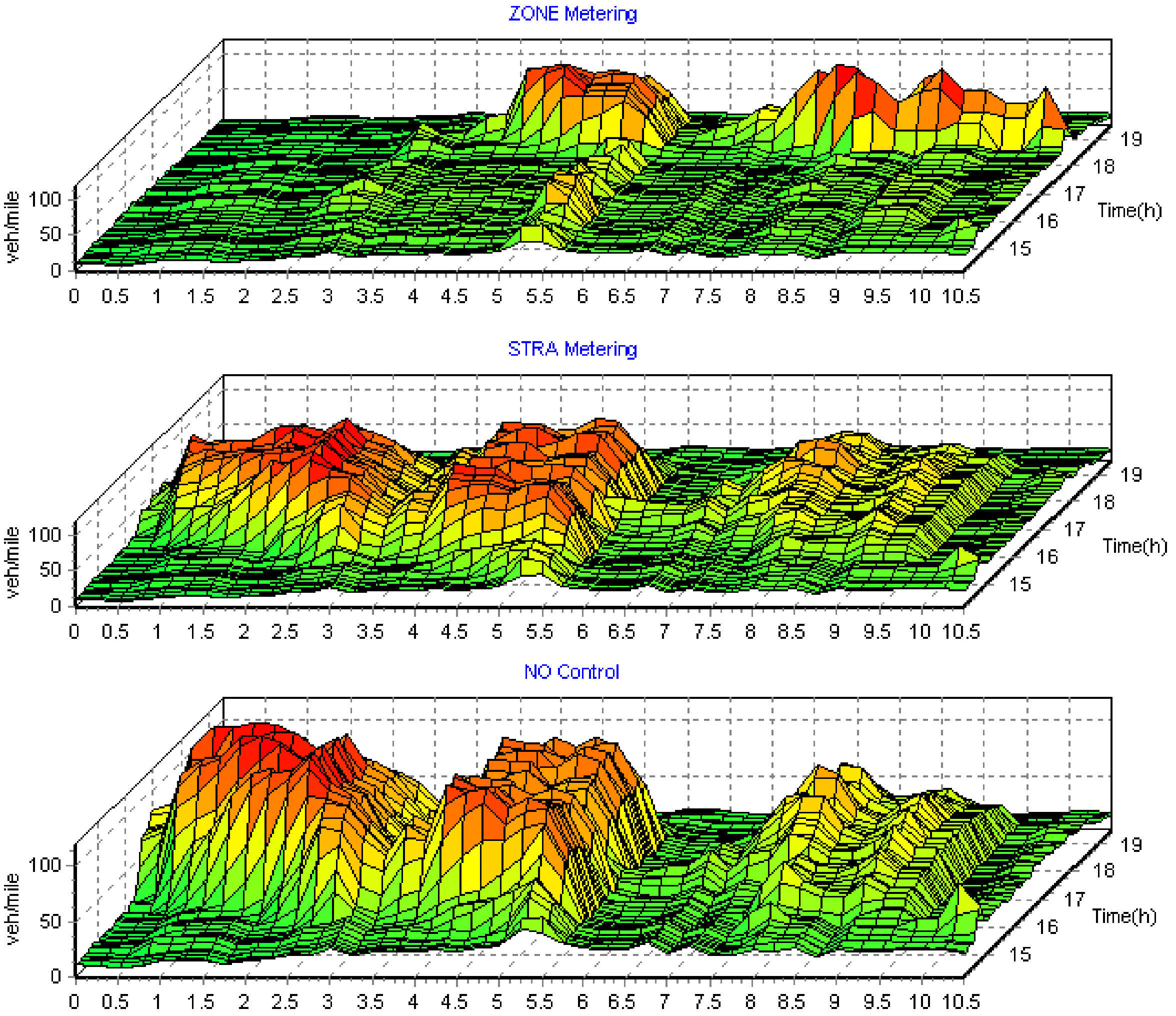


Figure A.27 TH169: Mainline Density Variation Nov 27th, 2000

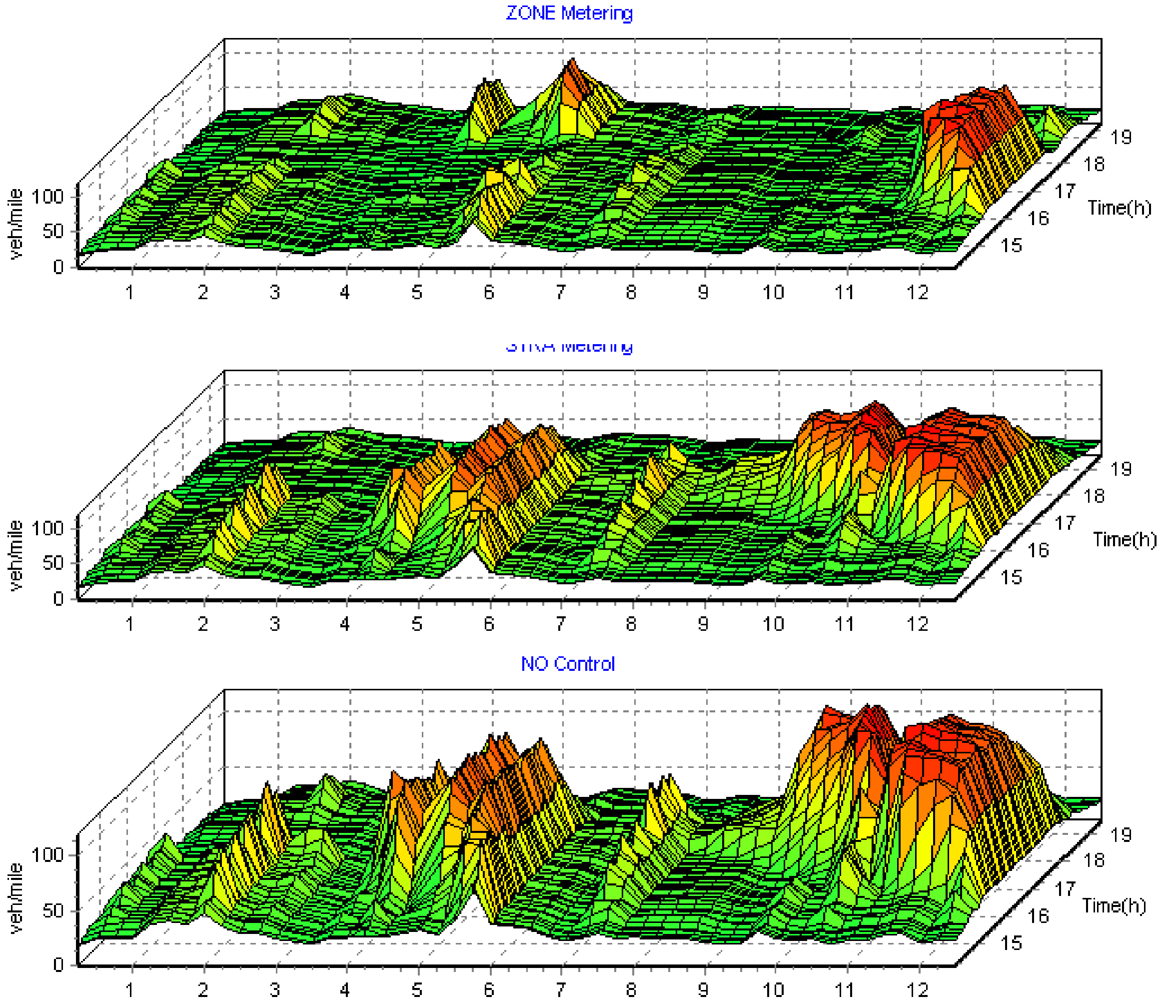


Figure A.28 I-94: Mainline Density Variation Oct 26th, 2000

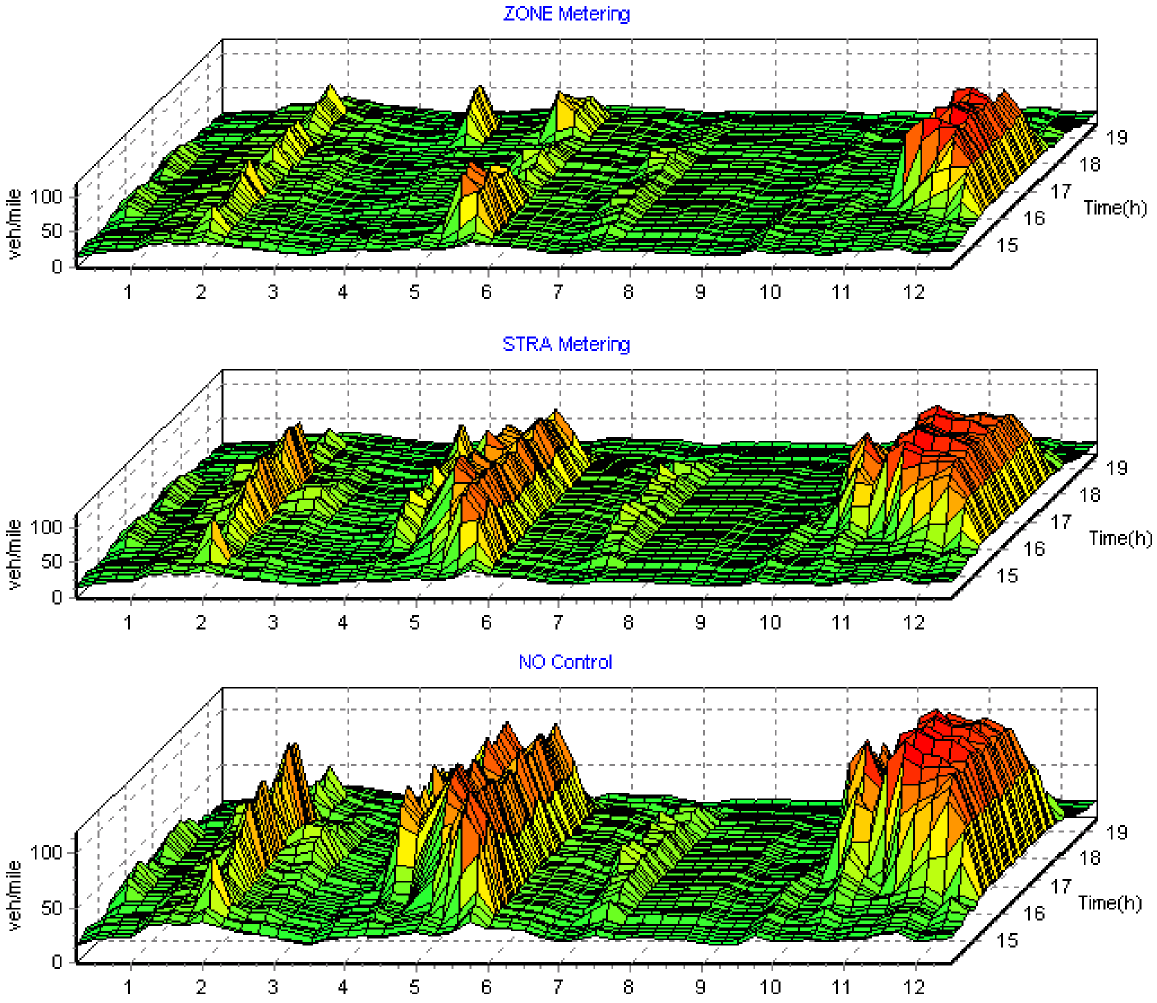
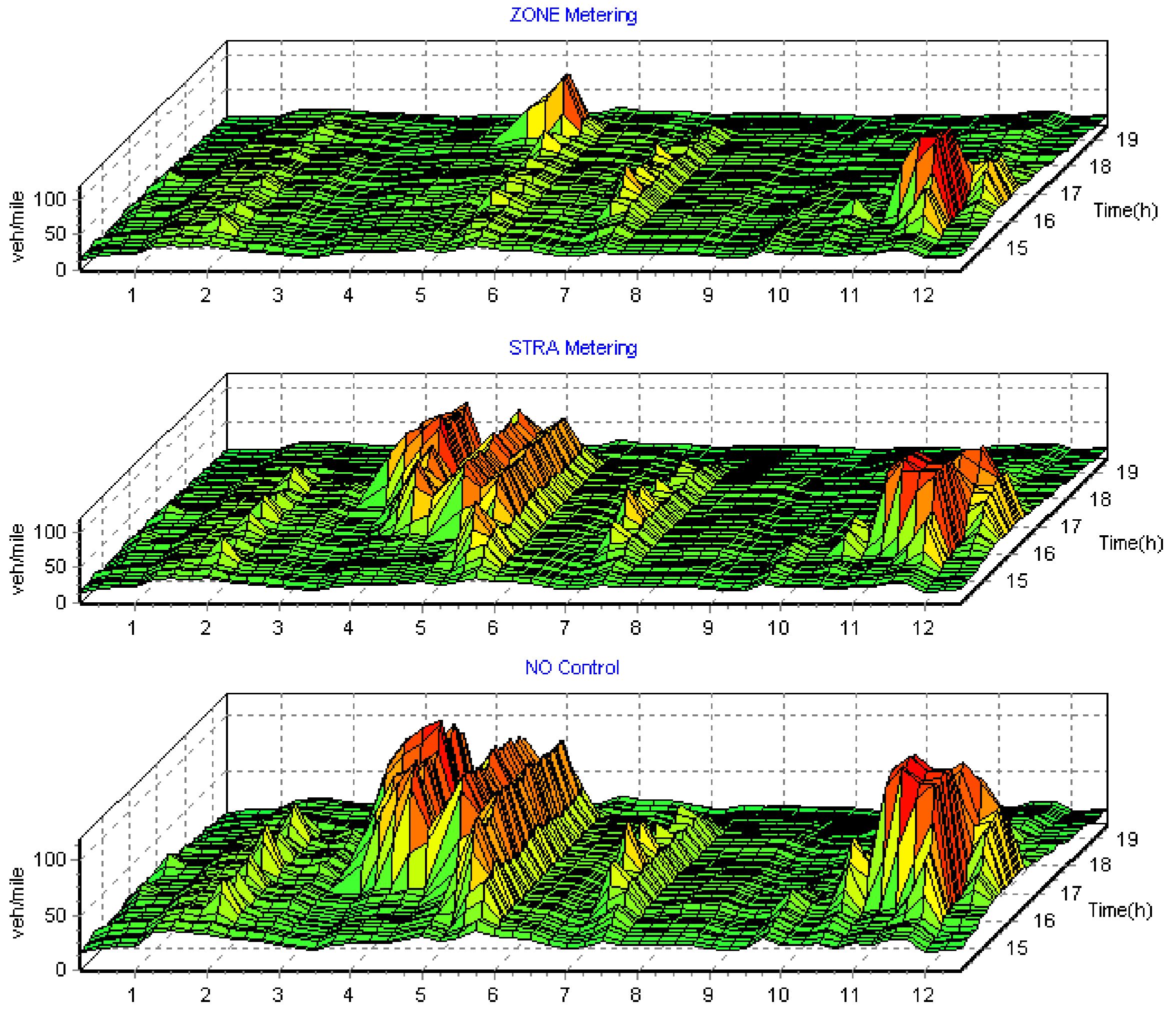


Figure A.29 I-94: Mainline Density Variation Nov 1st , 2000



ZONE Metering

STRA Metering

NO Control

Figure A.30 I-94: Mainline Density Variation Nov 27th, 2000

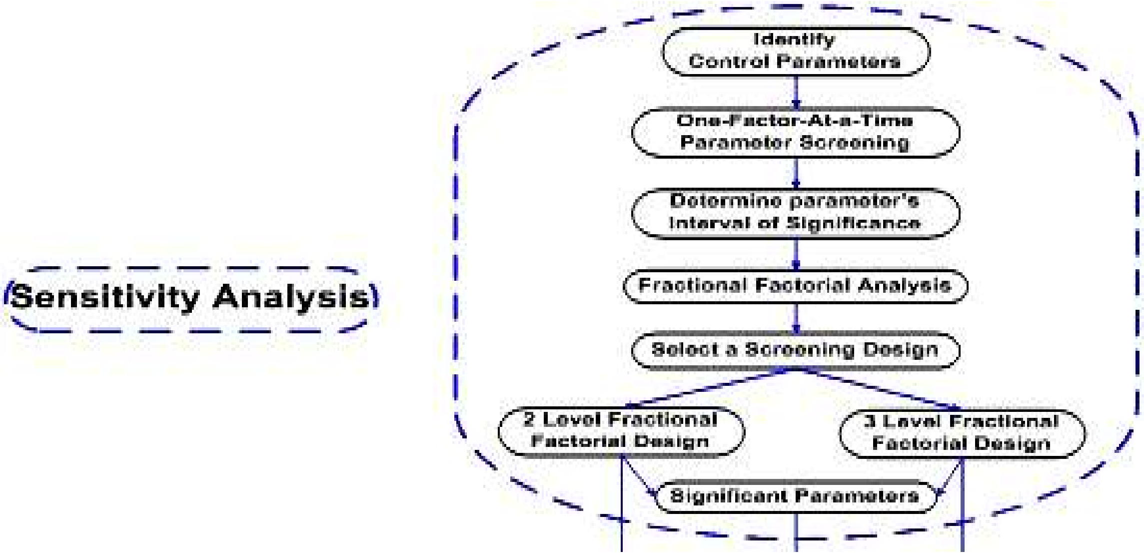
References

1. Arnold E.D (1998). "Ramp Metering: A Review of the Literature." Virginia Transportation Research Council. Report No. VTRC 99-TAR5.
2. Barceló, J., Ferrer, J.L. and Grau, R. (1994). AIMSUN2 and the GETRAM simulation environment. Internal report, Departamento de Estadística e Investigación Operativa. Facultad de Informática. Universitat Politècnica de Catalunya.
3. Bogenberger, K. and May, A.D. (1999). "Advanced Coordinated Traffic Responsive Ramp Metering Strategies." California PATH Paper *UCB-ITS-PWP-99-19.*
4. CAMBRIDGE SYSTEMATICS (2001). "Twin Cities Ramp Meter Evaluation." Final Report, Minnesota Department of Transportation, 2001.
5. Chaudhary, N.A. and Messer, C.J. (2000). "Ramp Metering Technology and Practice Task 1 and Task 2 Summary." Report No. FHWA/TX-00/2121-1.
6. Chang, T.H. and Li, Z.Y. (2002). "Optimization of mainline traffic via an adaptive coordinated ramp-metering control model with dynamic OD estimation." Transportation Research 10C: 99-120.
7. Chen C.-I., Cruz J.B. Jr. and Paquet J.G. (1974). "Entrance ramp control for travel rate maximization in expressways." *Transpn. Res*. 8, 503-508.
8. Chu, L. and Yang, X. (2003). "Optimization of the ALINEA Ramp-metering Control Using Genetic Algorithm with Micro-simulation." 82nd Transportation Research Board Annual Meeting, Washington D.C., 2004.
9. Elefteriadou, L. (1997). "Freeway Merging Operations: A Probabilistic Approach." Proceedings of the 8th International Federation of Automatic Control Symposium on Transportation Systems, Chania, Greece, pp. 1351-1356.
10. "GETRAM Extensions User Manual." TSS Transport Simulation Systems, 2003.
11. Hasan, M., Jha, M. and Ben-Akiva, M.E. (2002). "Evaluation of ramp control algorithms using microscopic traffic simulation." *Transportation Research* 10C: 229-256.
12. Hourdakis, J. and Michalopoulos, P.G (2002). "Evaluation of ramp control effectiveness in two Twin Cities freeways." 81st Transportation Research Board Annual Meeting, Washington D.C., 2002.
13. Hourdakis, J.,Michalopoulos, P.G. and Kottommannil, J. (2003). "A practical procedure for calibrating microscopic traffic simulation models." 82nd Transportation Research Board Annual Meeting, Washington D.C., 2003.

14. Isaksen L. and Payne H.J. (1973). "Suboptimal control of linear systems by augmentation with application to freeway traffic regulation." IEEE Trans. Automatic Control 18, 210-219.
15. *ITE Traffic Control Systems Handbook* ITE (1985). Institute of Transportation Engineers, pp. 4.18-4.23.
16. Lau. D. (2001). "Minnesota Department of Transportation: Stratified Metering Algorithm." Internal Report.
17. Lau R. (1996). "Mn/DOT Ramp Metering Algorithm." Internal Report, Minnesota Department of Transportation, Minneapolis, Minnesota, 1996.
18. May A. (1976). "A proposed dynamic freeway control system hierarchy." Control in Transportation Systems, Proceedings of the IFAC/IFIP/IFORS 3rd International Symposium, pp 1-12, Columbus, Ohio, August.
19. Papageorgiou, M. (1983). "Application of Automatic Control Concepts to Traffic Flow Modeling and Control." Springer, New York.
20. Papageorgiou M., Blossevillle J.-M and Habib, H.-S. (1990). "Modeling and Real-time control of traffic flow on the southern part of boulevard peripherique in Paris: Part II: Coordinated on ramp metering." *Transpn Res*.-A 24, 361-370.
21. Papageorgiou M., Habib H.S. and Blosseville J.M. (1991). "ALINEA: A local feedback control law for on ramp metering*." Transpn Res*. Rec. 1320, 58-64.
22. Papageorgiou, M., Hadj-Saem, H. and Midddelham, F. (1997). "ALINEA local ramp metering: summary of field test results." Transportation Research Board, 6th Annual Meeting, Washington, DC.
23. Payne H.J., Thompson W. A. and Isaksen L. (1973) "Design of traffic responsive control system for a Los Angeles freeway." *IEEE Trans. Systems. Man. And Cybernetics* smc-3, 213-224.
24. Payne H., Brown D., and Todd J.(1985). "Demand responsive strategies for interconnected freeway ramp control systems" Vol. 1: Metering strategies FHWA/RD-85/109,VERAC Incorporated, San Diego, California.
25. Robinson J. and Doctor M. (1989). "Ramp Metering Status in North America- Final Report." Report No. DOT-T-90-01, FHWA, U.S. Department of Transportation, Washington D.C.
26. Stephanedes, Y. and Chang, K.K. (1993). "Optimal control of freeway corridors." *ASCE Journal of Transportation Engineering* 119, 504-514.
27. Stroustrup, B. (1997). *The C++ Programming Language*. Third Edition, Addison-Wesley 1997.

28. Taylor M.A., Young W. and Bonsall P.W. (1996). *Understanding Traffic Systems: Data, Analysis and Presentation*. Avebury, England.
29. Texas Transportation Institute. (1999). “Urban Roadway Congestion Annual Report 1999.” College Station, TX: Texas A&M University.
30. Wang J.J. and May A.D. (1973). “Computer model for optimal freeway on ramp control.” *Highway Res.* Rec. 469, 16-25.
31. Wattleworth J. A. and Berry D.S. (1965). “Peak-period control of a freeway system-Some theoretical investigations.” Highway Res. Rec. 89. 1-25.
32. Wattleworth, J.A (1967). “Peak-period analysis and control of a freeway system.” *Highway Research Record* 157.
33. Xin, W., Michalopoulos, P.G., Hourdakis, J., and Lau, D. (2004). “Minnesota’s New Ramp Control Strategy: Design Overview and Preliminary Assessment.” 83rd Transportation Research Board Annual Meeting, Washington D.C., 2004.
34. Yuan L.S. and Kreer J.B. (1971). “Adjustment of freeway ramp metering rates to balance entrance ramp queues.” Transpn Res. 5, 127-133.
35. Zhang H., Ritchie S. and Lo Z. (1994). “A local neural network controller for freeway ramp metering.” Int. Fed. Automatic Control. Proc. 7th Symp. Transpn Sys. Theory and Applications Adv. Technol. August 1994, Tianjing, China.
36. Zhang H., Ritchie S. and Recker W. (1996). “Some general results on the optimal ramp control problem.” *Transpn Res* Part C Vol. 4, No. 2, pp. 51-69, 1996.
37. Zhang L. and Levinson D. (2003) “Optimal Freeway Ramp Control without Origin-Destination Information.” *Transportation Research* part B (in press).

Chapter 5: Sensitivity Analysis



Sensitivity Analysis (SA) is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation. The primary purpose of a sensitivity analysis is to increase our knowledge of the behavior of the system concerning changes in its parameters as well as the input conditions. Additionally, the sensitivity analysis is the first step towards parameter optimization.

One-Factor-At-a-Time (OFAT) analysis

OFAT sensitivity analysis, also known as threshold analysis (Critchfield and Willard, 1986), is one of the simplest ways of investigating the sensitivity of a model in the form of graphs, charts and/or surfaces. Generally, such a graphical method is used to give visual indication of how the output is affected by variations in the inputs (Geldermann and Rentz 2001).

As a first step of this preliminary sensitivity analysis, all the parameters of a control strategy and their applicable ranges are identified and a set of parameter values is selected as a reference (henceforward referred to as the base set). The method further requires defining a Sensitivity Index (e.g., percent change in MOE, rate of change in MOE). SI values are calculated by individually varying only one parameter across its range while holding all other parameters at their base values. Thus for each parameter a rough sensitivity curve is first developed using a coarse step size and if necessary is locally refined with a finer interval. A suitable threshold value of the SI is then selected and all the parameters that fall above (or below depending on the SI) are identified as most sensitive. Further, for each sensitive parameter an interval of significance is also identified.

OFAT is very useful screening technique and can expose complex dependencies between inputs and outputs (McCamly and Rudel, 1995). However, it addresses only a potentially small portion of the entire parameter domain. Further, parameter interactions are impossible to capture. Hence it is recommended here as a good practice to avoid using relatively high threshold values of SI.

Fractional Factorial Analysis

Factorial analysis, which is based on the principles of Design of Experiments (DOE), is an efficient approach to estimate the parameter effects and their interactions (Kleijinen, 1993 and Montgomery, 1997). It is an experimental strategy in which all parameters are varied together, instead of one at a time. Each parameter is allowed to take only a definite number of values referred to as levels. Typically a parameter is assigned not more than 5 levels. The main effect of a particular parameter is calculated as the change in response (e.g., MOE) due to a change in its level. If this difference in response between two levels of a parameter is not the same at all levels of another parameter, then the two parameters (hence forward referred to as *factors*) are said to have an *interaction*. In a full factorial analysis, all possible combinations of parameter levels are evaluated. Thus, a full factorial can estimate all two-factor and higher order interaction effects but generally needs astronomically large number of evaluations. For instance, for 10 parameters with 3 and 2 levels each will require 3^{10} and 2^{10} runs respectively. However, by reasonably assuming that higher order interactions are negligible, only a fraction of full factorial experiment is sufficient to estimate the main effects and lower order interactions. Such designs are termed as Fractional Factorial designs. The reduction in the number of evaluations is accomplished at the expense of "losing" information on main and interactions effects. This loss of information results from some main and interactions effects being entangled otherwise called "aliased" with other main and interactions effects. The effects that are entangled become inestimable as their combined effect can only be estimated from the design. The highest order of estimable interaction effects determines the Resolution of an experimental design. A design is of resolution R where no p-factor effects are aliased (or entangled) with any other effects of order less than R-p. A Roman numeral subscript is employed to denote design resolution. Thus, Resolution III designs are ones in which no main effects are aliased with any other main effect, but main effects are aliased with two-factor interactions and two-factor interactions may be aliased with each other. Resolution IV designs are the ones in which no main effect is aliased with any other main effect or with any two-factor interaction, but two-factor interactions are aliased with each other. Resolution V design are ones in which no main effect or two factor interaction is aliased with any other main or two-factor interaction, but two-factor interactions are aliased with three-factor interactions.

As it can be readily seen, the higher the resolution the better the design. However, as the resolution of design increases the number of evaluations required also increase. Therefore a good balance between loss of information and number of evaluation is required. In general, a resolution of V is considered excellent, IV adequate and III economical.

Another optional but supplementary criterion to use in search good fractional factorial designs is the minimum aberration criterion (Fries and Hunter, 1980), which is an extension of maximum resolution criterion (Box and Hunter, 1961). Technically, a minimum aberration design is defined as the design of maximum resolution which minimizes the number of pairs of aliased interactions of the crucial order. For example, a minimum aberration resolution IV design would have the minimum number of pairs of confounded interactions. Orthogonal designs allow independent estimation of all estimable effects and also minimize the variation the regression coefficients. For the objective of this study, it is recommended to use orthogonal Resolution V designs because at least a Resolution of five is required to estimate all two factor interactions and an orthogonal design is required to ensure that both the factors and their interactions are uncorrelated. A technical description of Fractional Factorial Design construction is beyond the scope of the thesis but detailed accounts on design constructions can be found in (Box and Hunter 1961, Franklin 1984 and Suen 1997). To avoid the laborious task of constructing FF designs, the National Bureau of Standards (1957) provided a comprehensive list of design tables that were constructed based on the minimum aberration criterion which is an extension of the maximum resolution criterion. These tables can be readily used for either 2 or 3 levels of the parameters.

Once an appropriate design is selected or constructed, for each parameter combination in the design matrix the control strategy is simulated on the test sites and performance MOEs are extracted. Using the selected MOE as a response, Analysis of Variance (ANOVA) needs to be conducted to estimate the significant main and interaction effects. Through ANOVA the null hypothesis that the parameters and their interactions have no effect on the observed responses is tested. Further relative importance of these effects can also be obtained by plotting a histogram of their standardized estimates.

IMPLEMENTATION TO SZM CONTROL STRATEGY

OFAT Analysis

The SZM control has twenty parameters as described in the Table 5.1. Throughout this study, the parameter values that are currently being used by Mn/DOT are considered as base values. Henceforward it is implicitly understood that this set defines the base case for all comparisons. As mentioned earlier, the primary MOE selected for this study was System Total Travel Time (STTT). Using percentage decrease in STTT from base case as a sensitivity index (SI), the sensitivity curves (rough or fine as required) were developed for all the parameters at both test sites TH-169 and I-94. A small threshold value of 0.5% was used to screen the parameters.

In spite of this seemingly small threshold most parameters were found insignificant leaving only nine significantly contributing to performance. Table 5.2 shows the intervals of significance of these parameters and the three levels (-1, 0, 1) selected for the further analysis. As expected, the sensitivity curves suggest that the control performance is non-linearly related to its parameters. For TH-169 and I-94 most of the curves exhibited similar overall trends, but their intervals of significance were shifted. This justifies the need for a site specific optimization of the control parameters.

Capacity estimates for the mainline (rightmost and other lanes), Maximum ramp waiting time threshold, Absolute Max. Release rate, etc strongly affect the system performance. Among the less sensitive parameters are the smoothing constants (for metered and un-metered ramp demand, mainline flow rate, etc.), Absolute Min. ramp release rate, etc. The following section explains the effects of changes in all the screened parameters and their observed trends in OFAT sensitivity analysis. Percent changes in System TTT, Mainline TTT and Ramp TTT from the base are plotted for both test sites with a base value of parameter being represented as a short vertical line.

No:	SZM Control Parameter	Notation	Units	Current Value	Applicable Range
1	Absolute Maximum Release Rate	R_{max}	Veh/hr	1714	1300 - 1714
2	Absolute Minimum Release Rate	R_{min}	Veh/hr	240	180 - 360
3	Increment to ramp demand	I_{ramp}	Veh/hr	150	80 - 240
4	Full Density of a zone	D_f	Veh/mile	32	23 - 40
5	Max. Allowed waiting time on Local ramps	$T_{max, L}$	Seconds	240	180 - 530
6	Max. Allowed waiting time on F-F ramps	$T_{max,F}$	Seconds	120	80 - 240
7	Queue Density equation-Intercept	$Q_{Intrecept}$	Veh/mile	206.715	200 - 240
8	Queue Density equation-Slope	Q_{Slope}	Hr/mile	0.03445	0.02 - 0.06
9	Capacity Estimate for Rightmost mainline lane	C_R	Veh/hr	1800	1700 - 2200
10	Capacity Estimate for Other mainline lanes	C_O	Veh/hr	2100	1800 - 3000
11	Occupancy Threshold	O_{Th}	%	25	12 - 46
12	Ramp Meter Turn off threshold	M_{off}	%	80	50 - 80
13	Ramp Meter Turn on threshold	M_{on}	%	85	50 - 100
14	Passage Compensate Factor	P_c	-	1.15	1.00 - 1.5
15	Accumulate Release rate smoothing factor	K_R	-	0.20	0.1 - 0.7
16	Queue Detector smoothing factor	K_D	-	0.15	0.1 - 0.7
17	Passage Detector smoothing factor	K_P	-	0.20	0.1 - 0.7
18	Mainline station smoothing factor	K_M	-	0.15	0.1 - 0.7
19	Unmetered station smoothing factor	K_U	-	0.15	0.1 - 0.7
20	Exit station smoothing factor	K_X	-	0.15	0.1 - 0.7

Table 5.1 SZM Control parameters and their applicable ranges

No:	Parameters for FF Design	Notation	Units	Factor Code	†Levels for TH169			†Levels for I94		
					-1	0	1	-1	0	1
1	Absolute Maximum Release Rate	R_{max}	Veh/hr	A	1540	1600	1660	1400	1520	1640
2	Occupancy Threshold	O_{Th}	%	B	20	30	40	20	30	40
3	Increment to Ramp demand	I_{ramp}	Veh/hr	C	120	150	180	150	180	210
4	Passage Compensate factor	I_{ramp}	Veh/hr	D	1.2	1.3	1.4	1.2	1.3	1.4
5	Ramp Meter Turn on Threshold	P_c	-	E	0.7	0.8	0.9	0.7	0.8	0.9
6	Capacity Estimate for Rightmost mainline lane	C_R	Veh/hr	F	1800	1950	2100	1750	1900	2050
7	Capacity Estimate for Other mainline lanes	C_O	Veh/hr	G	2100	2400	2700	2100	2400	2700
8	Full Density of a zone	D_f	Veh/mile	H	30	35	40	25	30	35
9	Max. Allowed waiting time on Local ramps	$T_{max, L}$	Second	J	240	330	420	300	390	480

Table 5.2 Screened SZM Parameters and Levels in Interval of Significance

Parameter Sensitivity Curves

Maximum Release Rate (R_{max}):

In the Twin Cities metro area, it has been a standard to meter ramps only if two or more storage lanes can be provided. In Dual-lane metering the controller operates by alternating the green-yellow-red cycle for each lane. Depending on the controller being used the cycle may or may not be synchronized. In the twin cities synchronized controlled ramps are designed to two lanes before the ramp meter but transitioned into one lane before merging the freeway. From a practical point of view, for a single lane ramp with one vehicle per green the smallest possible cycle is 4 seconds with 1 second green, 1 second yellow and 2 seconds red. This produces a maximum ramp release rate of 900 VPH. On the same lines, dual lane metering can provide a metering capacity of 1600 to 1700 VPH. The value currently used by MN/DOT is 1714 VPH which corresponds to a cycle time of 2.1 seconds (2 seconds for yellow plus green and 0.1 second for red). As any smaller cycle length than 2.1 seconds will be infeasible to drivers, the tested range of this parameter was from 1714 VPH to 1300 VPH. The sensitivity curves for both the test sites show that as R_{max} decreases from its base value Ramp TTT increases steadily as fewer and fewer vehicles are allowed to enter the mainline. However, Mainline TTT and System TTT are affected non-linearly with minimum mainline TTT occurring when R_{max} is in the neighborhood of 1600 and 1400 VPH for Th169 and I94 respectively. A lower value for I-94 can be attributed to the fact that it is more severely congested test site with the maximum release rate of a ramp depends on the test site and the congestion level.

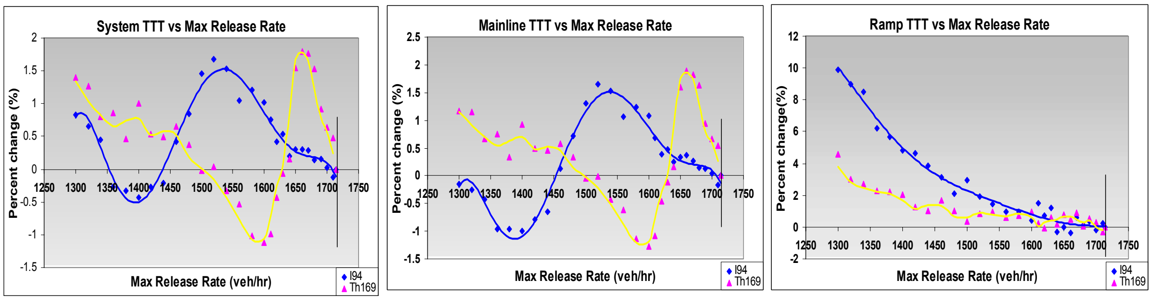


Figure 5.1 Effect of parameter Max Release Rate on Performance MOEs

Occupancy Threshold (O_{Th}):

Occupancy threshold is a control parameter that detects queues with the back of the queue approaching a queue detector. As this threshold increases, the theoretical storage space on a ramp increases thereby allowing larger queues and consequently high Ramp TTT. The current value of 25% used in SZM control is equivalent to an average density $(d = O_s * 52.80/ L_e)$ of 53 veh / mile. For both the test sites similar overall trend was observed. As expected, RTTT increases sharply from with the threshold value increasing from 15 % to 30% and then flattens between 30 % and 45%. However, STTT and MTTT decrease as O_{Th} changes from 20% to 30% and then increase when O_{Th} changes from 30% to 45%.

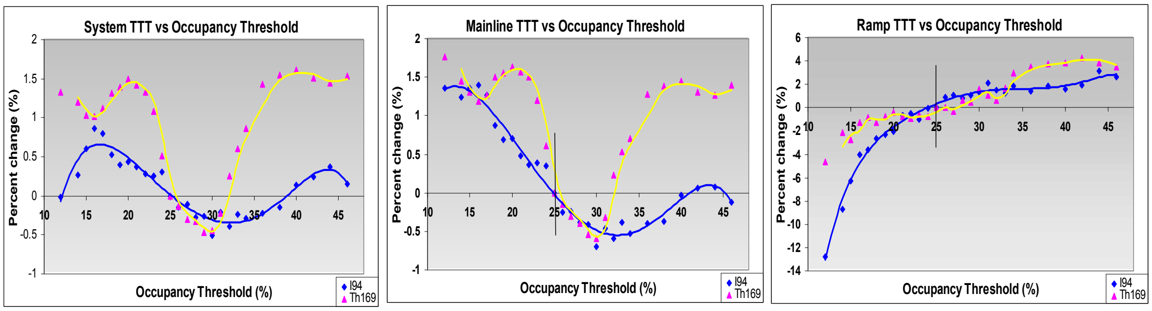


Figure 5.2 Effect of parameter Occupancy Threshold on Performance MOEs

Increment in Ramp Demand (I_{Ramp}):

When a ramp queue exceeds beyond the queue detector, the detector counts are no more accurate. To avoid such a condition, whenever the queue detector occupancy increases a predetermined threshold, ramp demand is increased by I_{Ramp} veh/hr for the next control period. Clearly for a given occupancy threshold as the value of this control parameter increases, the storage space available for the ramp queue decreases. Thus, the Ramp TTT decreases steadily. However, the effect on Mainline and System TTT is non-linear and also depends on the congestion level on the freeway. On the moderately congested site TH169 at lower increment values the MTTT like s the mainline TTT increases

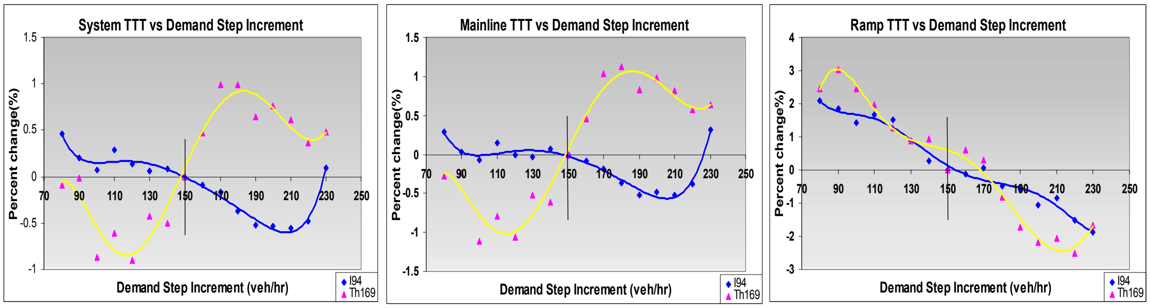


Figure 5.3 Effect of parameter Ramp demand Increment on Performance MOEs

Capacity Estimates (C_R & C_O):

Capacity estimates of rightmost lane and all other lanes are two parameters which are used in the determining the downstream mainline capacity of a zone (B). According to *Highway Capacity Manual* (HCM, 2000), the capacity of a freeway section should not be more than 2200 vphpl when the free flow speed is 65 mph. However, recent studies on the stochastic nature of freeway capacity (Polus and Pollatschek, 2002 and Persaud, 2001)) have shown that probability density function of freeway capacity follow shifted gamma distribution. The capacity of the rightmost lane is considerably lower than that of the middle lane which is also lower than the leftmost lane (assuming a 3-lane freeway section). The flows of the highest probability occur at 2100 veh/hr, 2375 veh/hr and 2800 veh/ hr on the rightmost, middle and left most lanes (Polus and Pollatschek, 2002). Moreover, very high flows up to 3000 veh/hr can also be reached on left most lanes but with very low probabilities. Thus, in this study a wide range of values was tested; a range of 1700 veh/hr to 2250 veh/hr for right most lanes and a range of 1800 veh/hr to 3000 veh/hr for other lanes were considered for the two parameters C_R and C_O.

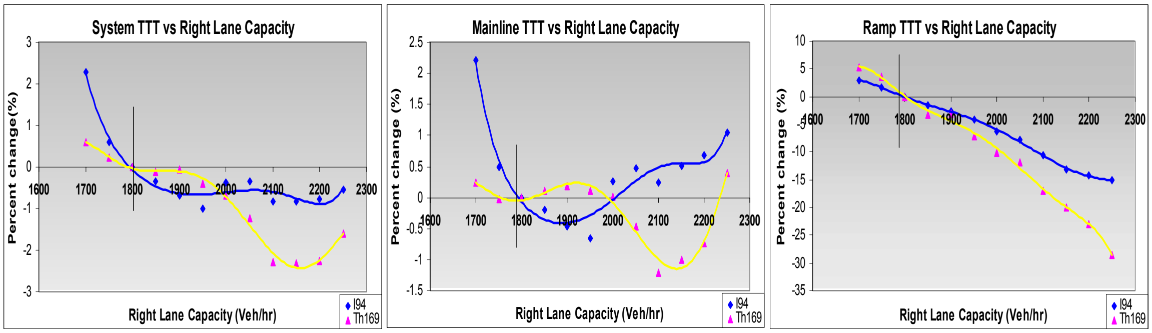


Figure 5.4 Effect of parameter Right lane capacity on Performance MOEs

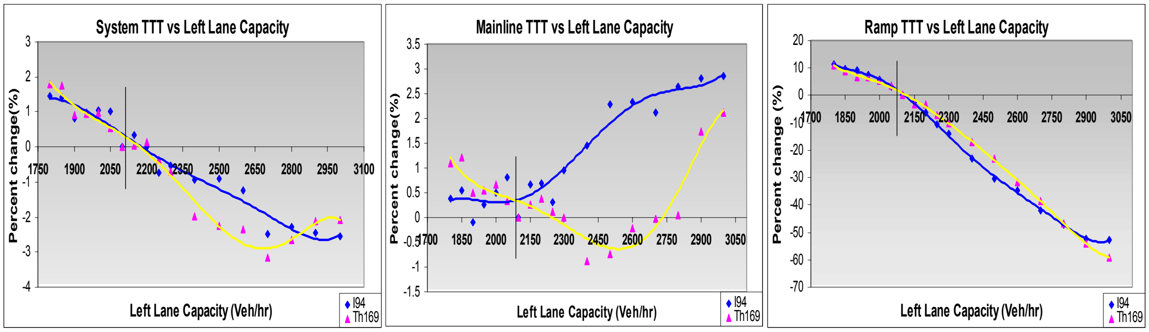


Figure 5.5 Effect of parameter Other-lane capacity on Performance MOEs

The sensitivity curves show that as the capacity estimates of right and other lanes increase the total allowed metered ramp flow increases in every zone. Thereby, less and less restrictive ramp release rates will be proposed resulting in lower ramp waiting time and Ramp TTT. This can be clearly noted as the case on both test sites irrespective of the level of congestion on the freeway. However, the effect on the mainline, and thus also on the system, differs significantly between the TH-169 and I-94. Figure 5.4 shows that the mainline of a moderately congested site like TH-169 can accommodate higher C_R values than its current default of 1800 veh/hr but will eventually deteriorate at values higher than 2100 veh/hr. On the other hand I-94 being a congested freeway, its mainline TTT starts to shoot up at a much lower C_R value of 1900 veh/hr as compared to TH-169. The system TTT decreases initially up to a C_R value of 2100 veh/hr and then increases sharply.

The effect of other lane capacity estimate C_O on the performance MOEs is similar to that of rightmost lane estimate C_R. However it has stronger effect as this estimate is used for more than one lane in a zone as compared to C_R. TH-169 has mostly 2-lane freeway sections but out of 12 miles more than 4 miles is 3-lane. I-94 is a mostly 3-lane freeway with some 4 and 5 lane sections. Being already congested, mainline of I-94 deteriorates for any value higher than the current default value of 2100 veh/hr. But, large improvements in RTTT offset this increase in MTTT, thereby improving the STTT. This is also consistent with TH-169, except that the between mainline performs better than the base scenario in between 2300 veh/hr and 2700 veh/hr.

Maximum Allowed Ramp Waiting Time (T_{max}):

T_{max} is the main control parameter that governs the queue control policy in SZM. In any case, the control logic maintains that the last vehicle in the estimated queue on a ramp is released within T_{max} . The current default value of T_{max} is 4 minutes (240 seconds) for all local access ramps. A wide range (180-520 sec) of this parameter was tested to capture its effect on all the three selected MOEs as shown in Figure 5.5. Ramp TTT keeps increasing with increase in T_{max} and it tends to reach a state where the ramps do not

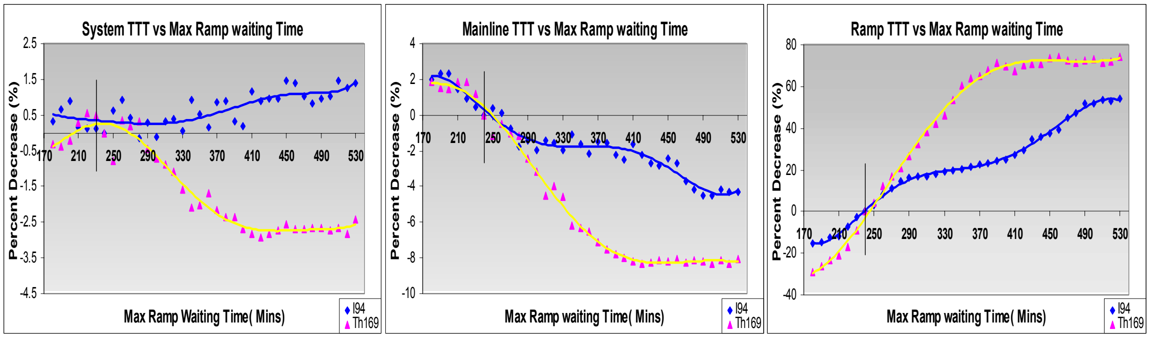


Figure 5.6 Effect of Maximum ramp waiting time on Performance MOEs

get any worse. However, this state occurred at two different values of T_{max} , 420 seconds and 480 seconds on TH-169 and I-94 respectively. In the case of Mainline TTT, TH-169 improves steadily as T_{max} is changed from 180 to 420 seconds, but further the improvements are marginal. In the case of I-94, which carries heavier volumes of traffic, similar trends are observed but with a lower improvement and at a higher cost of total waiting time on the ramps. Overall, the System TTT of I-94 increases with T_{max} as the mainline improvements are offset by the increase in the Ramp TTT. However, TH-

169 exhibits considerable decrease in System TTT between the values 240 and 420 as shown in Figure 5.6.

Full Density of a Zone (D_f):

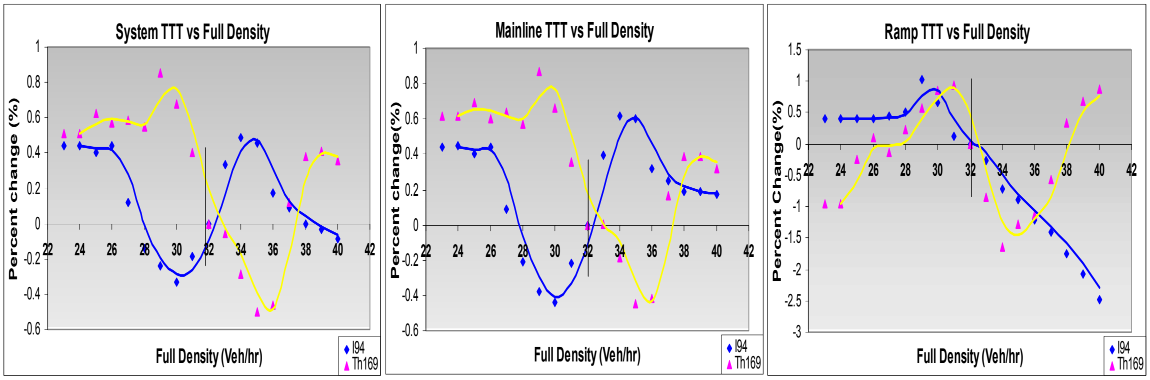


Figure 5.7 Effect of parameter Full density on Performance MOEs

The parameter full density of a zone reflects the available space within a zone. The current default value is 32 veh/mile (corresponds to 15% occupancy). As the parameter value increases more spare capacity on the freeway is available. Thus the RTTT continues to decrease. Mainline and System TTT of I-94 is unaffected small values of D_f. However in the interval between 26 and 40 a minimum and a maximum occurs. TH169 also has exhibits similar trend but with a shifted interval of 30 and 40. Minimum STTT and MTTT occur at a higher value of D_f (~ 36 veh/mile) in the case of TH169. This is because of the low densities on the mainline of TH169 which helps the SZM control to allow more vehicles to merge from the ramps.

Passage Compensation Factor (P_c):

In the absence of a queue detector, which is sometimes the case, a passage detector is used to replace the queue detector measurements. However, as mentioned earlier, these counts do not represent the true ramp demand. Thus, this empirical parameter compensates for this error by multiplying counts of the passage detector by a factor greater than 1.0. The current default value is 1.1. The range of values that were tested for P_c is between 1.0 and 1.5. As both the sites have situations where a queue detector is missing, very similar trends are observed. Clearly, the RTTT is affected strongly as it decreases with increase in P_c. Mainline TTT and System TTT experience minimum values at approximately a value of 1.3. Thus, an interval of 1.2 -1.4 was selected for next stage of analysis.

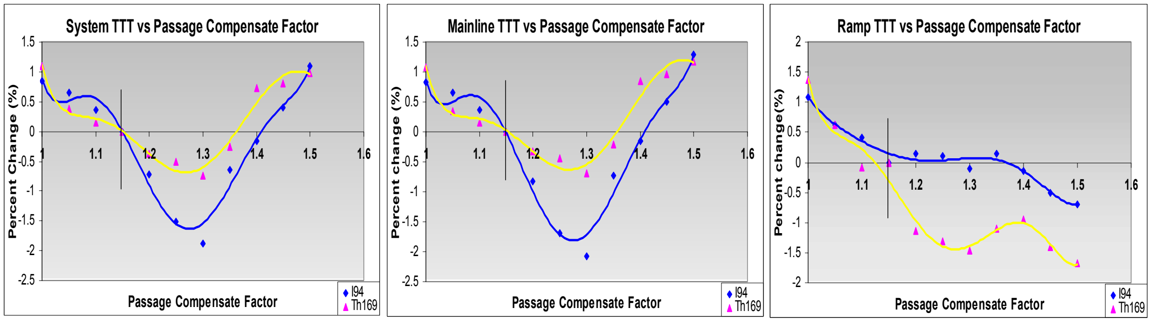


Figure 5.8 Effect of Passage compensate factor on Performance MOEs

Ramp Meter Turn-on threshold (M_{on})

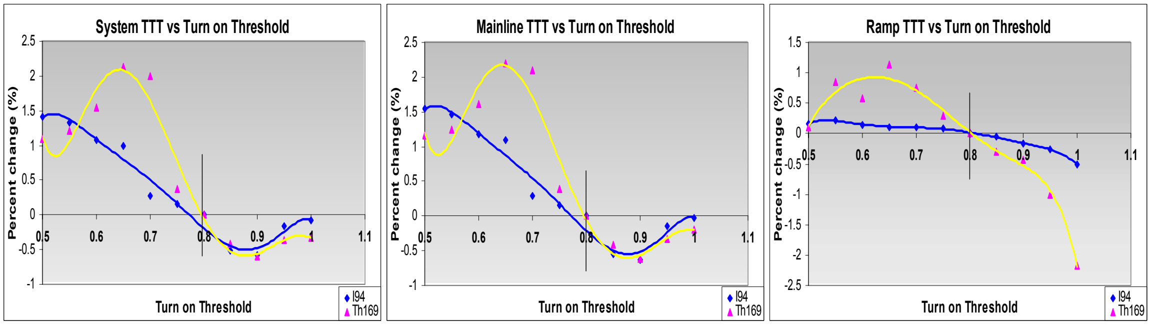


Figure 5.9 Effect of parameter Turn-on threshold on Performance MOEs

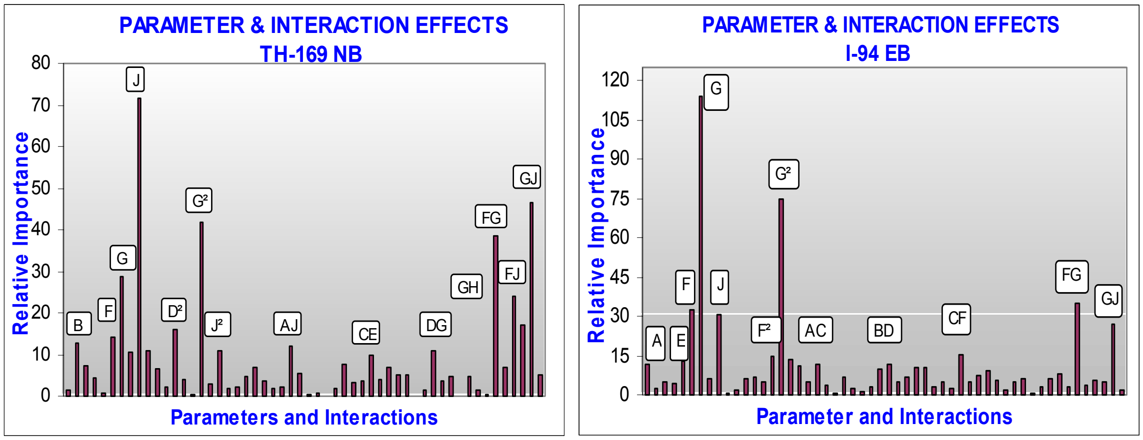
Even before the meter begin operation the accumulated release rate (R_a) is calculated from the release rates proposed by the algorithm. After the start time, a meter will begin operation when the ramp demand is greater than M_{on} times the accumulated release rate. This is to ensure that the ramp demand is high enough to warranty metering. Thus, in this experiment M_{on} had been tested over a range of 0.5 to 1.0, while the current default value is 0.80. The plots in Figure 5.9 show that operating at a slightly higher threshold than the present practice will produce improvements in all the performance MOEs. This is consistent with both the test sites.

Fractional Factorial Analysis

Considering the nonlinearity of the sensitivity curves, in order to capture the curvature effects three levels are selected for each parameter within its interval of significance. Thus for 9 parameters a full factorial would have required 3^9 (=19683) evaluations. With a 3_V^{9-4} Fractional Factorial Design the number of evaluations is reduced to 243, which is only a 1/81 fraction of the full factorial. The selected design is orthogonal and has a resolution V. With 10 replications at each design point, for each site the whole experiment required 250 computer hours (~10 days) on a Pentium PC.

Significant Parameters and Interactions

The results from ANOVA with System TTT as response were obtained for the two test sites. It should be noted that ANOVA has to be conducted on standardized parameters with their levels coded between -1 and 1 as shown in Table 5.2. Figure 2.10 illustrates the relative importance of the nine control parameters and their interactions using their coefficient estimates in the ANOVA. The analysis shows that the Capacity estimate for the rightmost lane (F), Capacity estimate for other lanes (G) and Maximum allowed ramp waiting Time (J) are highly significant to system performance of SZM control. Moreover, they exhibit strong mutual interactions. Hence, the choice of these parameter values is not trivial and only specific combinations might produce an optimal performance. Further, G and J also exhibit quadratic effects. Among the other parameters, Maximum release rate (A), Occupancy Threshold (B) and Meter Turn on Threshold (E) are also statistically very significant depending on the test site. Moreover, it is worth noting that at 90% confidence level all the parameters are found significant in either directly as a main effect or in the form of an interaction with other main effects.



A - Absolute Max Release Rate ; B - Occupancy Threshold ; C - Step Increment in ramp demand
D - Meters turn on Threshold ; E - Passage Compensate factor ; F - Right lane Capacity
G - Other lane Capacity ; H - Full Density of a zone ; J - Max. Ramp wait time

Figure 5.10 Standardized Parameter and Interaction Effects on STTT

Chapter 6: EFFECT OF EXTERNAL FACTORS

As is well known, demands can vary widely from the expected levels, for which a control strategy is designed to accommodate, affecting the performance of ramp metering algorithms. Incidents (non-recurrent congestion) further complicate matters raising questions concerning the robustness and reliability of ramp control. Consequently, the effects of such external factors on the performance of SZM control were also studied and are presented in this section.

Uniform Demand Change

The effect of uniform demand changes were taken into account by assuming a percentage of the typical day demand used in this study to represent below normal to normal congestion levels. For each demand level, simulations were conducted with the currently used control parameter values. At all entrance ramps and also the upstream mainline station, the volume counts are increased by a percentage of the test day's demand and the new states are generated in the simulator. To take care of the stochastic nature of the results ten replications are simulated and random seeds are kept the same throughout the experiment.

Results

Figures 6.1 and 6.2 present the effect of uniform change of demand level on the two test sites as a percentage of the change from the No-Control case.

Th-169

Figure 6.1 shows that, according to the System TTT, the SZM strategy has considerable fluctuation in performance. It exhibits a localized increase in performance around the normal demand level but reduces when extremely low or high levels are present. The Mainline TTT exhibits similar fluctuations but it is clearly superior to the No-Control case except in very high demand levels. Again, the highest performance is exhibited around the usual demand levels.

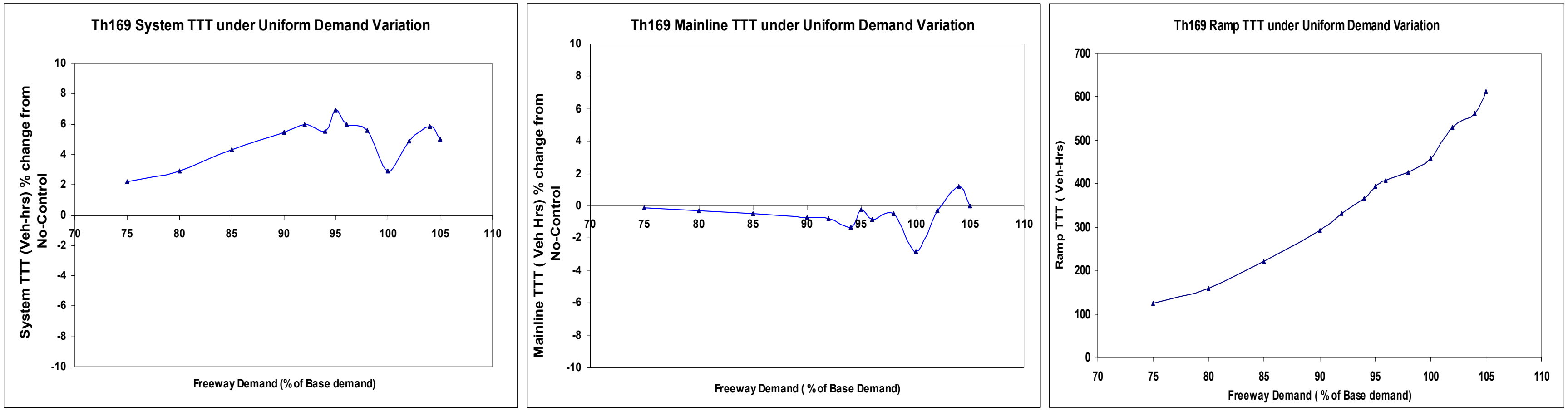


Figure 6.1 Effect of Uniform Demand Variation on TH-169

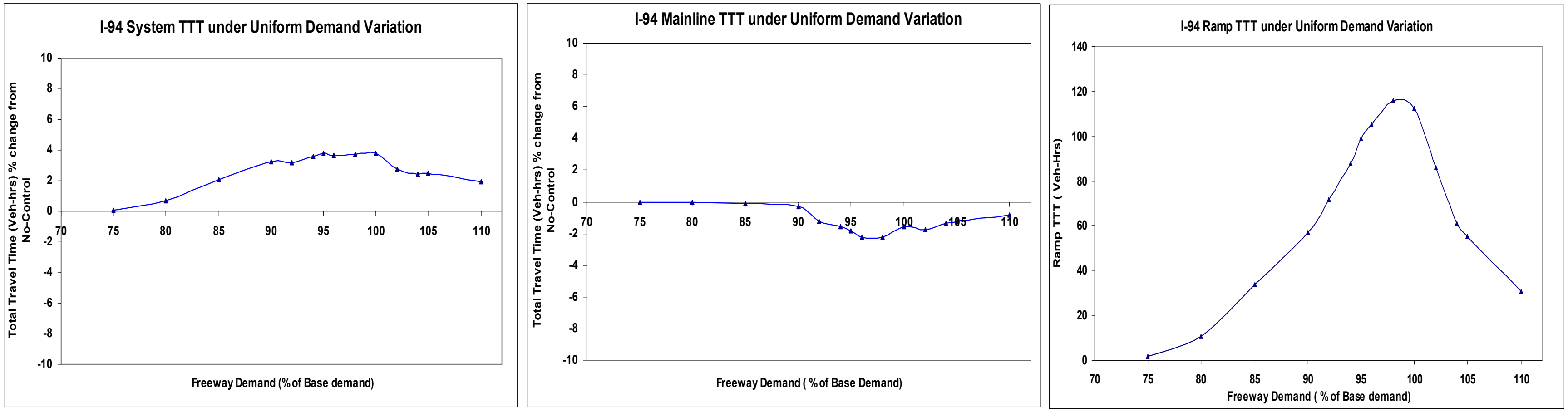


Figure 6.2 Effect of Uniform Demand Variation on I-94

Ramp TTT is increased almost linearly as the demand level increases.

I-94:

The behavior on I-94 is slightly different as presented in Figure 6.2. In respect to System TTT, There is minimum fluctuation with the worst performance being around the normal demand levels. This can be a byproduct of the day selection implying that the I-94 system is optimized for higher than normal conditions (not unusual in this roadway). The reason such a behavior is encountered can be explained by the Ramp TTT which has a considerable peak around the normal demand level. It is worth noting here that, in difference to TH-169, on I-94 the majority of traffic enters the site from the mainline and not the ramps. The experiment conducted increased uniformly the demand on the ramps resulting in a better balance between ramps and mainline.

Effect of Incidents

A freeway incident is defined as any planned or unplanned event that affects the traffic flow on the roadway (Sethi, et al., 1994). Some examples of freeway incidents include accidents and crashes, disabled or abandoned vehicles, vehicle fires, weather events, road debris, construction, etc. The highway Capacity Manual (TRB 1994) states that incidents disrupt the level of service; reduce capacity radically; and present hazards to motorists, particularly those directly involved. Past researchers have estimated that non-recurrent congestion due to freeway incidents accounts for one-half to three-fourths of the total congestion on metropolitan freeways in the U.S. Capacity is also reduced during incidents due to lane closure or impediments. The duration of an incident is one of the most appropriate measures that indicate the severity of an incident and the consequent deterioration of level of service on the freeway. Earlier studies analyzed freeway incidents and modeled incident duration as a random variable and attempted to fit probability density functions to the data. Golob et al. (1987) theorized that duration of an incident can be modeled according to a lognormal distribution. Giuliano (1989), Garib et al. (1997) and Sullivan (1997) have also supported the use of a lognormal distribution to describe freeway incident duration. Similar distributions like log-logistic distribution (Jones et al. 1991) and Weibull distribution (Nam and Mannering, 2000) were also proposed. The notable aspect of these distributions is a shift to the left that shows a larger proportion of short-duration incidents. For the two test sites TH-169 and I-94, the probability density curves of incident duration are plotted in figures 6.3 and 6.4 using historical data obtained from Mn/DOT incident database. The figures suggest that the incident duration distributions of both test sites closely follow log normal distribution.

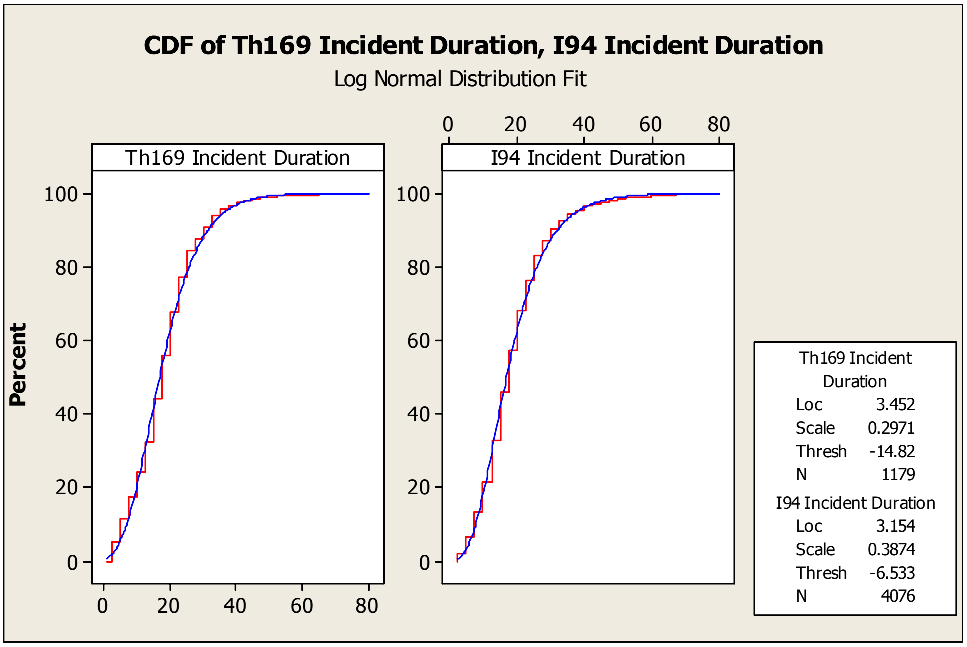


Figure 6.3 Lognormal fit of I94 & Th169 Incident Duration Cumulative Density Function

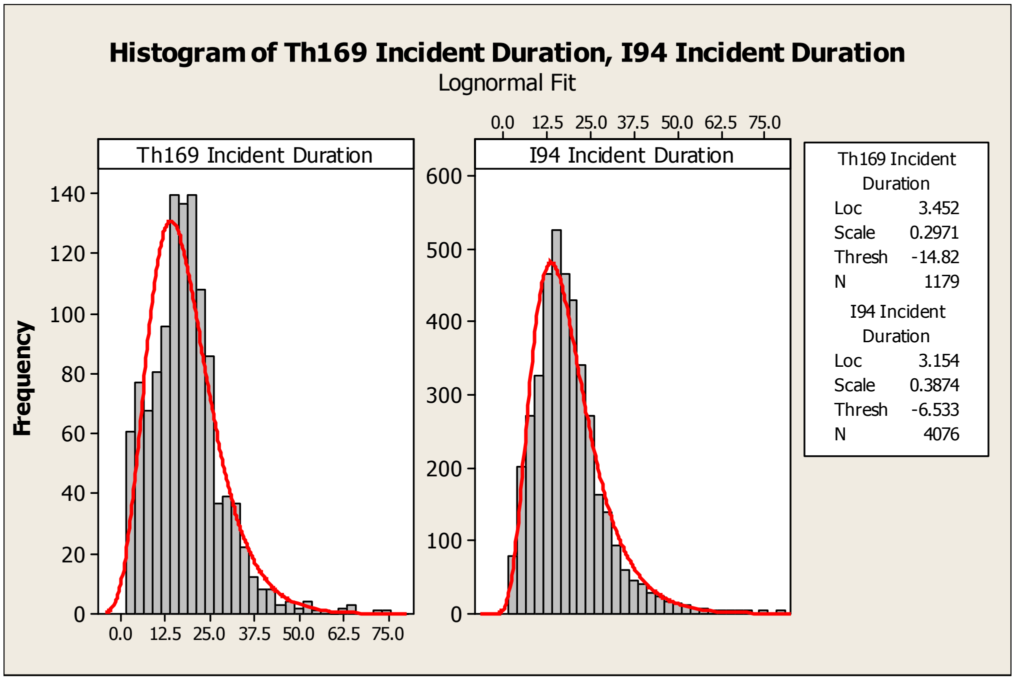


Figure 6.4 Lognormal fit of I94 & Th169 Incident Duration Probability Density Function

The probability density function and the cumulative density function are fitted in MINITAB® using multiple distributions (Normal, Gamma and Weibull) but a lognormal distribution is found to give the best fit in accordance with the findings from the previous studies. The implication of this in the domain of the present study is that 20-minute incidents are most frequent and there are practically no incidents that last longer than an hour. Thus, effect of incidents with durations between 0 and 60 minutes was only studied here.

The effect of incidents on the performance of SZM control was studied by designing artificial incidents in the microscopic simulator. In AIMSUN incidents are assumed to cause blockage of lane(s) over a certain period of time. An incident is defined if its location, lane, time of occurrence and duration are specified. On each test site two hypothetical incident locations were selected, such that they are downstream and upstream of a recurrent bottleneck, as they usually occur. To maintain consistency in the evaluation, each incident was designed to occur on the rightmost lane and start at 17:00:00 Hrs as suggested by Mn/DOT. The effect of each such incident was individually tested under several severity levels. Specifically, as incident duration was the selected measure of incident severity, in this experiment it was varied over a range from 10 minutes to 60 minutes as suggested from the incident duration distributions. The increment interval was selected to be 10 minutes to ensure significantly different scenarios. The selected bottleneck on Th169 is near the on ramp from I-394 WB. The artificial incident upstream of the bottleneck is located on the mainline between the on-ramps from I-394 EB and I-394 WB, while the downstream incident is located between I-394 WB ramp and Th55 EB ramp. Similarly, the selected bottleneck location on I-94 is near the on-ramp from Huron Boulevard. The upstream incident is located on the mainline between Riverside and Huron Boulevard ramps; while the downstream incident is located between Huron and TH-280. All incidents are within one-half a mile (next mainline detector station) from the bottleneck location. Figures 6.4, 6.5, 6.6 and 6.7 show the effect of incidents, upstream and downstream of the bottleneck on TH-169 and I-94. As expected the mainline, ramp and system total travel time increase steadily as incident duration increases.

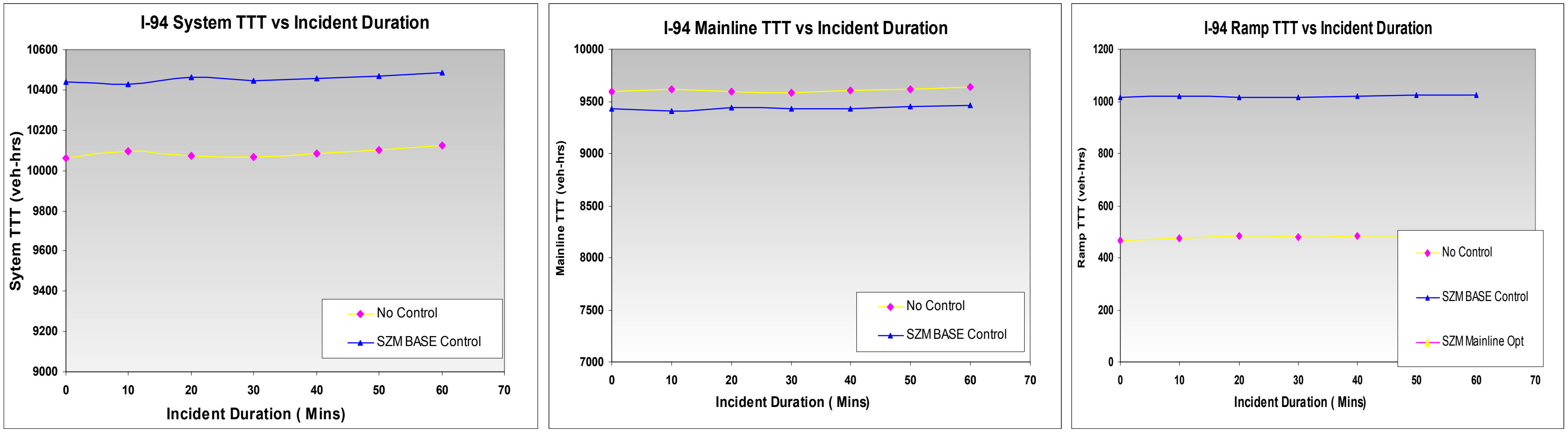


Figure 6.5 Effect of Upstream Incident on I-94

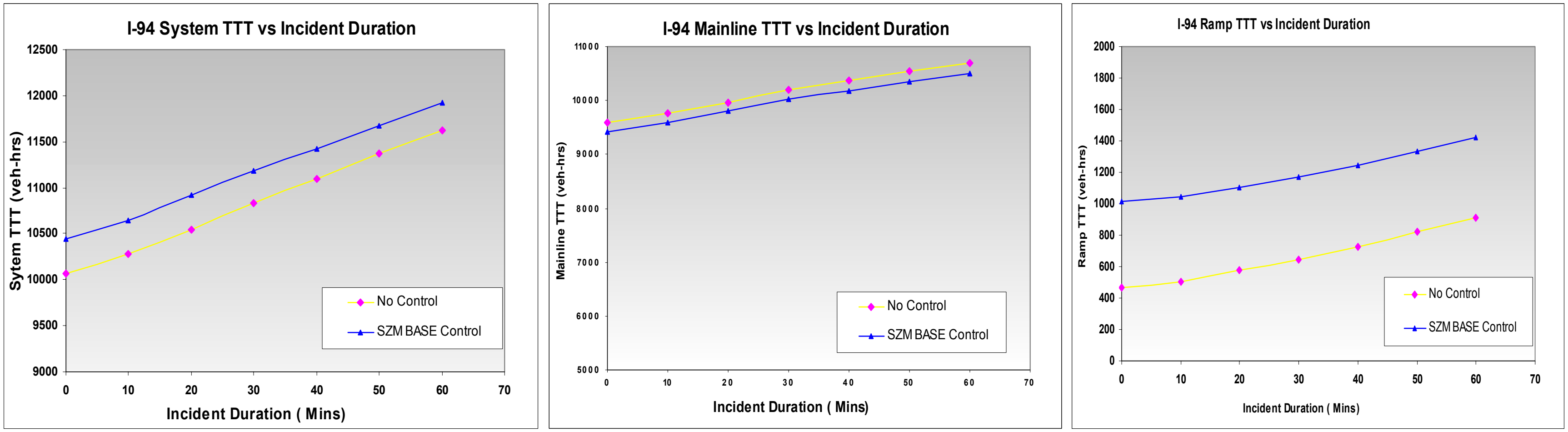


Figure 6.6 Effect of Downstream Incident on I-94

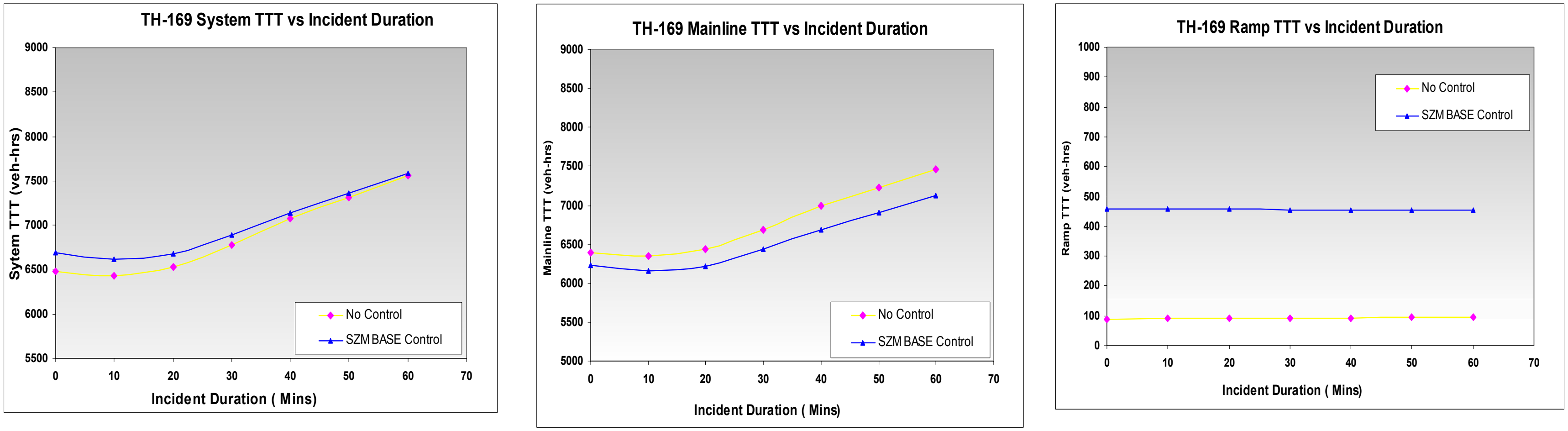


Figure 6.7 Effect of Upstream Incident on TH169

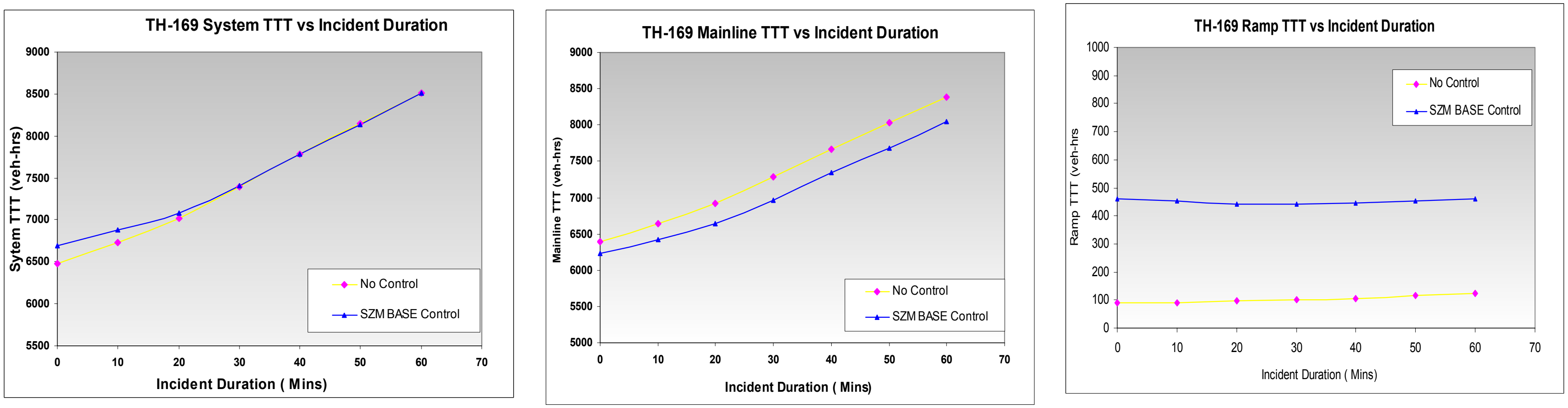


Figure 6.8 Effect of Downstream Incident on TH169

In an upstream incident, vehicles experience a drop in capacity at the incident primarily due to the bottleneck downstream to it. Therefore, the capacity drop due to the incident is practically zero. Thus, eventually the vehicles pass the bottleneck at the same time whether or not there is an incident. This is strongly supported by the results from microscopic simulation as shown in above figures. On the other hand, in the case of a downstream incident vehicles released from the bottleneck are delayed further due to incident downstream to the bottleneck. Thus, localized delay of the incident is accentuated due to the capacity reduction of the active bottleneck. In essence, an incident downstream to a bottleneck is more detrimental to control performance than an upstream incident.

The significance of incidents near recurrent bottlenecks has to be recognized by all Departments of Transportation. Once an incident is detected, it should be categorized according to their location, severity and duration and should respond to it accordingly. Allocation of resources as well as selection of surveillance equipment and incident clearance strategies. Separate surveillance system should be used in the areas close to bottlenecks. California's Department of Transportation already practices this by employing special surveillance system with anticipating stationary trucks rather than floating trucks to detect and remove traffic incidents near bottlenecks.

References

1. ITS America. (1995). National ITS Program Plan, Washington, DC.
2. Federal Highway Administration. (1990). Highway Statistics, Washington, DC.
3. Papageorgiou, M., Hadj-Saem, H. and Midddelham, F. (1997). “ALINEA local ramp metering: summary of field test results.” *Transportation Research Board*, 6th Annual Meeting, Washington, DC.
4. Elefteriadou, L. (1997). “Freeway Merging Operations: A Probabilistic Approach.” Proceedings of the 8th International Federation of Automatic Control Symposium on Transportation Systems, Chania, Greece, pp. 1351-1356.
5. Operation TimeSaver. (1996). “Intelligent Transportation Infrastructure Benefits: and Experienced.” FHWA, US Department of Transportation.
6. Pearce, V. (2000). What have we learned about ITS? Chapter 2: What have we learned about Freeway Incident and Emergency Management and Electronic Toll Collection? Technical Reports & Papers, US Department of Transportation.
7. Zhang, M., Kim T., Nie X., Jin W., Chu L., and Recker W. (2001). „Evaluation of On-ramp Control Algorithms.” *California PATH Research Report* UCB-ITS-PRR-2001-36.
8. Xin, W., Michalopoulos, P.G., Hourdakis, J., and Lau, D. (2004). “Minnesota’s New Ramp Control Strategy: Design Overview and Preliminary Assessment.” 83rd Transportation Research Board Annual Meeting, Washington D.C., 2004.
9. Wattleworth, J.A. (1967). “Peak-period analysis and control of a freeway system.” *Highway Research Record* 157.
10. Papageorgiou, M. (1983). “Application of Automatic Control Concepts to Traffic Flow Modeling and Control.” Springer, New York.
11. Stephanedes, Y. and Chang, K.K. (1993). “Optimal control of freeway corridors.” *ASCE Journal of Transportation Engineering* 119, 504-514.
12. Zhange, H., Ritchie, S., and Recker, W. (1996). “Some general results on the optimal ramp metering control problem.” *Transportation Research* C 4, 51-69.
13. Chang, T.H. and Li, Z.Y. (2002). “Optimization of mainline traffic via an adaptive coordinated ramp-metering control model with dynamic OD estimation.” *Transportation Research* 10C: 99-120.

14. Bogenberger, K. and A.D. May. (1999). "Advanced Coordinated Traffic Responsive Ramp Metering Strategies." California PATH Paper *UCB-ITS-PWP-99-19.*
15. Hasan, M., Jha, M. and Ben-Akiva, M.E. (2002). "Evaluation of ramp control algorithms using microscopic traffic simulation." *Transportation Research* 10C: 229-256.
16. Chu, L. and Yang, X. (2003). "Optimization of the ALINEA Ramp-metering Control Using Genetic Algorithm with Micro-simulation." 82nd Transportation Research Board Annual Meeting, Washington D.C., 2004.
17. Park, K and Carter, B. (1995). "On the effectiveness of genetic search in combinatorial optimization." Proceeding of the 1995 ACN symposium on Applied Computing.
18. Goldberg, D.E. (1989). *Genetic Algorithm in Search. Optimization and Machine Learning*. Addison-Wesley Pub. Co., Inc.
19. CAMBRIDGE SYSTEMATICS (2001). "Twin Cities ramp Meter Evaluation." Final Report, Minnesota Department of Transportation, 2001.
20. Lau. D. (2001). "Minnesota Department of Transportation: Stratified Metering Algorithm." Internal Report.
21. Box, G. E. P. and K. B. Wilson (1951). "On the experimental attainment of optimum conditions." *Journal of Royal Statistical Society, Series B* 13 (1): 1-38.
22. Barceló, J., Ferrer, J.L. and R. Grau (1994). *AIMSUN2 and the GETRAM simulation environment.* Internal report, Departamento de Estadística e Investigación Operativa. Facultad de Informática. Universitat Politècnica de Catalunya.
23. Gipps, P.G. (1986). "A model for the structure of lane-changing decisions." *Transportation Research* B 20B(5) 403-414.
24. Hourdakis, J. and Michalopoulos, P.G. (2002). "Evaluation of ramp control effectiveness in two Twin Cities freeways." 81st Transportation Research Board Annual Meeting, Washington D.C., 2002.
25. Critchfield, G.C., and Willard, K.E. (1986). Probabilistic Analysis of Decision Trees Using Mote Carlo Simulation, Medical Decision Making, 6(1):85-92.

26. Geldermann, J., and Rentz, O. (2001). Integrated Technique Assessment with Imprecise Information as a Support for the Identification of Best Available Techniques (BAT), *OR Spektrum*, 23(1):137-157.
27. McCamley, F., and R.K. Rudel (1995). “Graphical Sensitivity Analysis for Generalized Stochastic Dominance.” *Journal of Agricultural and Resource Economics*, 20(2):403-403.
28. Kleijnen, J. P. C (1993). “Experimental design for sensitivity analysis, optimization, and validation of simulation models.” In J. Banks, editor, *Handbook of Simulation*. Wiley, New York.
29. Montgomery, D.C (1997). *Design and Analysis of Experiments*. Wiley and Sons Ltd.: New York.
30. Fries A and Hunter W.G. (1980). “Minimum aberration 2^{k-p} designs.“ *Technometrics* 22: 601-608
31. Box G. E. P. and Hunter J. S. (1961). “The2^{k-p} fractional factorial designs.” *Technometrics* 3: 311-351,449-458.
32. Franklin, M.F. (1984). “Constructing tables of minimum aberration p^{n-m} designs.” *Technometrics* 26:225–232.
33. Suen C., Chen H., Wu C.F.J. (1997). “Some identities on q^{n-m} designs with application to minimum aberration designs.” Ann Statist 25:1176–1188.
34. National Bureau of Standards (1959). “Fractional Factorial experiment designs for factors at two and three levels.” *Applied Mathematics* Series 54. US Government Printing Office, Washington.
35. Franklin M.F. (1984). “Constructing tables of minimum aberration p^{n-m} designs.” *Technometrics* 26:225–232.
36. Suen C., Chen H., Wu C.F.J. (1997). “Some identities on q^{n-m} designs with application to minimum aberration designs.” Ann Statist 25:1176–1188
37. Myers R.H. and Montgomery D.C. (1995). *Response Surface Methodology, Process and Product Optimization Using Designed Experiments.* Wiley Series.
38. Box, G.E.P. and Behnken, D.W. (1960). “Some new three-level designs for the study of qualitative variables.” *Technometrics* 2, 455-475.

39. Craney, Trevor A. and Surles, James G. (2002). "Model-dependent variance inflation factor cutoff values." **Source:** *Quality Engineering*, v 14, n 3, 2002, p 391-403
40. Highway Capacity Manual (2000). Transportation Research Board, National Research Council, Washington, D.C.
41. Polus, A. and Pollatschek, M. (2002). "Stochastic Nature of Freeway Capacity and its Estimation." *Canadian Journal of Civil Engineering*, Vol 29: pp. 842-852, 2002.
42. Stat-Ease, (2003). Design-Expert® 6 User's Guide, Stat-Ease, Inc. 2003.
43. J.A. Nelder, R. Mead (1965). "A Simplex Method for Function Minimization." *Computer Journal* **7:** 308-323.
44. Cook, R. D., and Weisberg, S. (1999). "Applied Regressional Analysis Computing and Graphics." New York: Wiley.