Evaluation of Ramp Control Algorithms using A Microscopic Traffic Simulation Laboratory, MITSIM

by

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Submitted to the Department of Civil and Environmental Engineering
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Abstarct

Ramp metering has emerged as an effective freeway control measure to ensure efficient freeway operations. A number of algorithms have been developed in recent years to ensure an effective use of ramp metering. As the performance of ramp metering depends on various factors (e.g. traffic volume, downstream traffic conditions, queue override policy etc), these algorithms should be evaluated under a wide range of traffic conditions to check their applicability and performance and to ensure their successful implementation. In view of the expenses of and confounding effects in field testing, simulation plays an important role in the evaluation of such algorithms.

This thesis presents an evaluation study of two ramp metering algorithms: ALINEA and FLOW. ALINEA is a local control algorithm and FLOW is an area wide coordinated algorithm. The purpose of the study is to use microscopic simulation to evaluate systematically how the level of traffic demand, queue spillback handling policy and downstream bottleneck conditions affect the performance of the algorithms. It is believed that these variables have complex interactions with ramp metering. MITSIM microscopic traffic simulator is used to perform the empirical study. It is argued that an explicit modeling of merging behavior is necessary for an appropriate evaluation of ramp control algorithms and therefore, a microscopic simulation model should be used.

The study consists of two stages. In the first stage, key input parameters for the algorithms were identified and calibrated. The calibrated parameters were then used for the second stage, where the performance of the algorithms were compared with respect to three traffic variables mentioned above using an orthogonal fraction of experiments. It was observed that for many of the scenarios, particularly at low demands, metering significantly increased system travel time. However, with proper calibration, the algorithms improved mainline as well as ramp conditions at high demands. A ramp queue storage length smaller than the physical length of the ramp was found to produce better performance. Regression analysis was used to identify the impacts of some of the interactions among experimental factors on the algorithms' performance, which is not otherwise possible with a tabular analysis. These results provide insights which may be helpful for design and calibration of more efficient ramp control algorithms.

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Chapter 1

Introduction

In recent years, significant emphasis has been given to the applications of advanced information and communication technologies in transportation. This has motivated researchers to develop new freeway control methodologies. These methodologies have been used in different parts of the world under the context of Intelligent Transportation Systems (ITS). One of the most popular and effective freeway control measures is ramp metering. This thesis presents an evaluation study of two ramp metering algorithms.

The study uses microscopic traffic simulation to evaluate the performance of ramp control algorithms with respect to key input parameters for the Central Artery/Tunnel (CA/T) network in Boston. This chapter provides a motivation for this research by first reviewing the traffic congestion problem and then discussing the remedial measures. The research objective is then outlined and the organization of the thesis presented.

The use of private automobile has grown consistently in the United States and throughout the world in the recent years. When many drivers want to take advantage of increased mobility simultaneously, it may produce undesirable effects such as congestion, pollution etc. Freeway congestion has been increasing substantially for the past few decades. According to *Highway Statistics* (Federal Highway Administration, 1990), the annual urban freeway delay in the United States is estimated at 2 billion vehicle hours. The value of lost productivity due to congestion is $100 billion a year in the United States alone (ITS America, 1995). Approximately, 66% of all carbon monoxide (CO) emissions are generated by automobiles. Increasing congestion also reduces highway safety. Each year, there are on an average, 41,000 deaths and 5 million injuries on U.S. freeways. Additionally, traffic accidents cost the U.S. an estimated $70 billion in lost wages and other direct costs annually (ITS America, 1995). All of these concerns make congestion alleviation a major transportation priority.

1.1 Causes of Congestion

Traffic congestion is a common phenomenon during peak periods, even without any incident. The phenomenon can be explained with the help of the underlying relationship between fundamental traffic variables. Traffic density, ρ is defined as the number of cars per unit length of the roadway, and traffic volume, q as the number of cars passing a given section in a unit time. Under steady-state conditions, these two traffic variables are related to each other as described by the fundamental diagram (Fig 1.1) of traffic engineering. The maximum volume that can pass through a roadway section is called capacity and is denoted by q_{max}. The density corresponding to the capacity is ρ_{cr} and is called critical density.

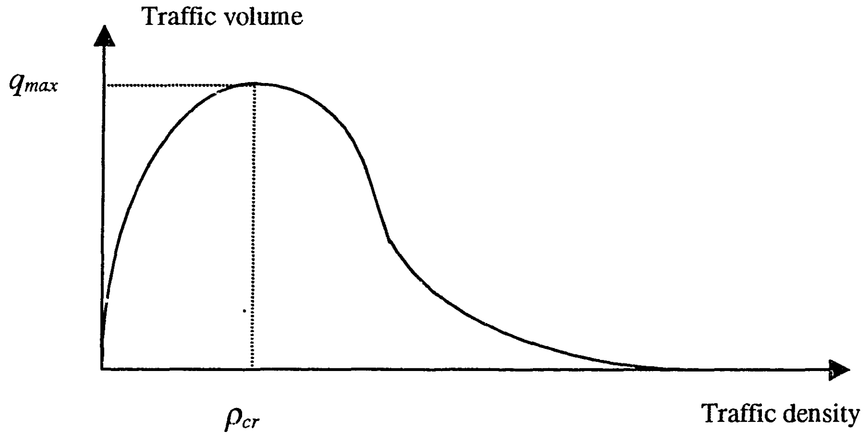

Fig 1.1. The Fundamental Diagram

The area under this curve can be divided into two regions. The region to the left of the critical density, ρ_{cr} represents non-congested traffic, while the region to the right represents a congested condition. Ideally, we would like traffic to operate in the left region. The freeway is best utilized at ρ_{cr}, when traffic volume achieves a maximum value q_{max}. Figure 1.1 shows that increase of density above the value ρ_{cr} on a freeway stretch leads to a corresponding decrease of traffic volume that reaches zero for $\rho = \rho_{jam}$ (the jam density at which traffic is stopped). This type of congestion due to excessive demand, i.e. $\rho > \rho_{cr}$, is called *recurrent* congestion. The precise values of q_{max}, ρ_{cr}, and ρ_{jam} depend on the freeway geometry (slope, number of lanes etc.), vehicles' characteristics, and driver behavior. The other type of congestion caused by the capacity reducing incidents is called *non-recurrent* congestion.

1.2 Possible Control Measures

The traditional approach of building new roads to solve the congestion problem is expensive, disruptive to existing traffic, opposed by numerous environmental groups, and constrained by scarce land availability. Consequently, alternative solutions aimed at effective utilization of existing systems have gained much attention in last few decades. It has been realized that many traffic problems can be resolved by influencing (controlling) traffic flow by using various traffic control measures. The underlying idea is to try to *"move with finesse instead of brute force"*. There have been several attempts both on theoretical and practical levels towards development of freeway traffic control systems. Several studies (Newman et. al., 1969, Moscowitz, 1973, Klijnhout, 1985) have indicated a high potential for cost-effective amelioration of traffic congestion, if control measures are applied suitably.

The possible control measures can be divided into two classes (Papageorgiou, 1983):

1) *Control measures affecting density* – Congestion can be avoided if density is maintained below ρ_{cr}. Thus traffic density can be affected -
   - by metering the entering traffic volumes, and/or
   - by diverting traffic upstream of the congestion.
2) *Control measures affecting the fundamental diagram* – Variable message signs such as speed limit signs, "keep your lane" signs etc. are known to increase the capacity in the fundamental diagram, if applied appropriately.

In this thesis, we will be concerned exclusively with ramp metering for freeway traffic.

1.3 Ramp Metering

Ramp control, or ramp metering, has been recognized as one of the most effective ways for combating freeway congestion. The entering traffic to the freeway from on-ramps is regulated so that the flow on the freeway does not exceed the capacity. The ramp meter also helps break the *"platoon"* of entering vehicles, resulting in an efficient merging operation.

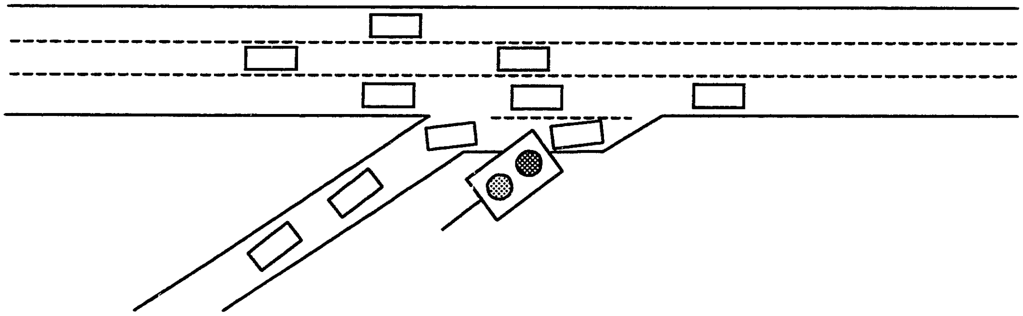

Fig 1.2. A Freeway On-Ramp with Meter.

Ramp control can potentially be used to –

- Utilize freeway capacity.
- Reduce extent and duration of recurrent congestion.
- Reduce the occurrence of non-recurrent congestion.
- Reduce average travel times.
- Divert traffic.

Ramp metering can also be used as a component of incident management system. According to the Minnesota Department of Transportation (MnDOT), "the use of ramp metering is an ITS development which provides the single greatest boost to freeway capacity and safety" (ITS International, 1997).

Several attempts have been made in the past toward the development of efficient ramp control strategies. Different methods have been proposed to calculate the metering rate that determines the rate of vehicles allowed to enter the freeway from the on-ramps. These strategies can be broadly divided into two categories: local control and area wide control.

- *Local Control (Isolated):* In this case, the metering plan is based on locally measured traffic conditions. Metering rate for one controller is not affected by that for others nor by traffic conditions elsewhere. So, this type of control is most suitable when there is local congestion in the vicinity of the metered ramp. But in case of multiple congestion spots in different parts of the network, this type of control will not be able to identify them and as a result may not be effective.

- *Area Wide Control (Coordinated):* For this type of control, there is a coordination in metering rate calculation among different controllers in the network. The control parameters for a set of controllers in the area are estimated in order to achieve a system-level objective.

Another similar ramp control system that combines both local and area wide strategy is known as *hierarchical control.* In this approach, there is a system-wide model at the upper level that calculates the desired network states, and a local controller at the lower level that adjusts the metering rate to minimize the difference between actual and desired network states (Chen et al. 1997).

Based on traffic responsiveness, ramp metering can be classified as :

- *Fixed Time Metering:* The metering rate for ramp meters is fixed for different times of the day. It is usually calculated based on historic traffic data.
- *Traffic Responsive Metering:* The metering rate is calculated based on real time traffic conditions in the network.

The concept of ramp metering is not new. Its use dates back to the 1960s. It was first implemented on the Congress Street (now Eisenhower) Expressway in Chicago in September 1961. Since then a number of states in North America namely – California, Texas, New York and Minnesota have been using ramp metering as a freeway control measure, albeit without any standard practice. The lack of standards may be due to the fact that a wide variety of practices are effective (ITS International, 1997). More recently, ramp metering is also gaining popularity in Europe. It is successfully used in Amsterdam, Paris and Glasgow (Papageorgiou, 1983).

1.4 Objective

This thesis presents a detailed simulation evaluation of the following two algorithms: a local ramp metering algorithm called ALINEA (Papageorgiou et al. 1991) and an area-wide heuristic algorithm called FLOW (Jacobson et al. 1989). The performance of ramp metering depends on various factors such as traffic volume, downstream traffic conditions, and policy of handling queue spillbacks. These variables have complex interactions with ramp metering. To the best of our knowledge, there has been no study that has identified the effect of downstream bottleneck or queue spillback policy on metering performance till date. In this study, we systematically investigate the performance of the ramp metering algorithms with respect to all these variables. In order to identify these effects, one has to perform either field tests or simulation experiments. Considering that it may not be possible to control the above mentioned variables (for example downstream condition) in the field, simulation provides an ideal alternative approach to evaluate the performance of ramp control algorithms over a range of values for those variables.

A significant contribution of this thesis lies in a detailed and elaborate experimental design of ramp metering evaluation with respect to several key variables that have not been tested before. Furthermore, the majority of the simulation based evaluation studies have been performed with macroscopic traffic simulators. Field data has strongly demonstrated a complex nature of traffic pattern in and around merging areas (Cassidy et al. 1998, Hall et al. 1990). Traffic flow in merging areas is emergent from a complex interaction between mainline and ramp traffic and depends on several factors including directional demand, driver behavior, road geometry and such. Macroscopic simulators are based on a coarse representation of traffic flow that fails to represent the said interactions. Thus, macroscopic simulators may not be adequate to evaluate the performance of ramp control algorithms. We use a microscopic simulation laboratory, called MITSIM laboratory, for evaluating ramp control algorithms. Our motivation to use MITSIM laboratory lies in an explicit modeling of merging behavior, which is critical for evaluation of ramp metering strategies.

MITSIM laboratory consists of a microscopic simulator that is responsible for moving traffic, and a traffic management simulator that is responsible for simulating control operations. It is designed for the evaluation of Dynamic Traffic Management Systems. A brief description of the MITSIM laboratory is presented in Chapter 3 (see Ben-Akiva et al. 1997 for details). In the simulator, vehicles are moved based on car following and lane changing behavior that have been calibrated and validated with a large amount of data from various sites (Ahmed, 1998). MITSIM laboratory is used to evaluate how the level of traffic demand, queue handling policy and downstream bottleneck conditions affect the performance of ramp metering and derive insights from the evaluation results.

1.5 Organization of Thesis

This chapter provided the basic concept of ramp metering as a freeway control measure. It described the motivation and the objective of our evaluation study. A literature review of existing ramp metering studies is presented in Chapter 2. Chapter 3 describes the evaluation methodology and provides a brief description of the two algorithms, the calibration of the input parameters and the experimental design adopted in this study. The fourth chapter summarizes the results and findings of the evaluation study. Finally, Chapter 5 presents a summary, conclusion and future work in this area.

Chapter 2

Literature Review

A literature review of the major works in the field of ramp metering is presented in this chapter. Local ramp control systems are reviewed in the first section followed by a review of area wide ramp control. Finally, evaluation methods and results of different ramp control strategies are discussed.

2.1 Local Ramp Control

A local ramp control system considers an isolated section of the network and the controller responds only to the changes in the local conditions. Figure 2.1 depicts schematically a local traffic control system for a freeway section. The following traffic flow variables can be used to represent a typical local ramp control system:

(a) O_{out} and O_{in} are the occupancy rates downstream and upstream of the on-ramp respectively,
(b) q_{out} and q_{in} are the traffic volumes downstream and upstream of the on-ramp respectively,
(c) r is the on-ramp traffic volume,
(d) r_{min} is the minimum on-ramp traffic volume that is to be allowed to enter, and
(e) q_{cap} is the capacity of the downstream section.

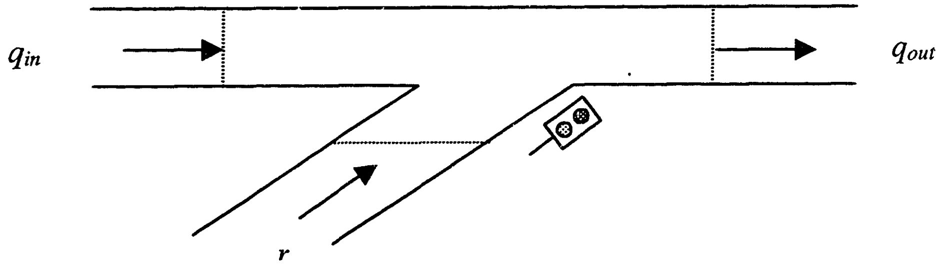

Fig 2.1. Local Ramp Metering Variables.

Local control strategies can be classified into following categories :

2.1.1 Fixed Time Control

Fixed time controls are static in nature. They do not depend on real time surveillance data. In this method, the cycle lengths are based on "time of day" and are usually calculated based on historic traffic data (Blosseville, 1985).

2.1.2 Demand-Capacity Strategy

This strategy, extensively used in the United States (Masher et al., 1975, Koble et al., 1980), is based on measuring the volume (q_{in}) upstream of the merge area and comparing this with the capacity (q_{cap}) of the downstream section of the merge area. Occupancy, O_{out} from the downstream detector stations is used to identify the congestion on the freeway. If the occupancy is above a preset threshold, congested condition is assumed to exist and the minimum metering rate r_{min} is used. If occupancy is below the threshold value, the upstream volume is compared with the capacity and the metering rate is determined by –

$$r = \begin{cases} Max(q_{cap} - q_{in}, r_{\min}) & if\ O_{out} \le O_{cr} \\ r_{\min}, & otherwise \end{cases} \tag{2.1}$$

2.1.3 Percent-Occupancy Strategy

This strategy (Masher et al., 1975, Koble et al., 1980) recognizes that there is no need to specify freeway capacity, as occupancy is a sufficient measure to identify congestion. Only upstream (of the on-ramp) occupancy measurements are used. The final form of the percent-occupancy strategy is shown in Figure 2.2. The critical value of the upstream occupancy is typically based on historical data and the transition value is found by trial and error in accordance with the historical on-ramp demand (Hadj Salem et al., 1988).

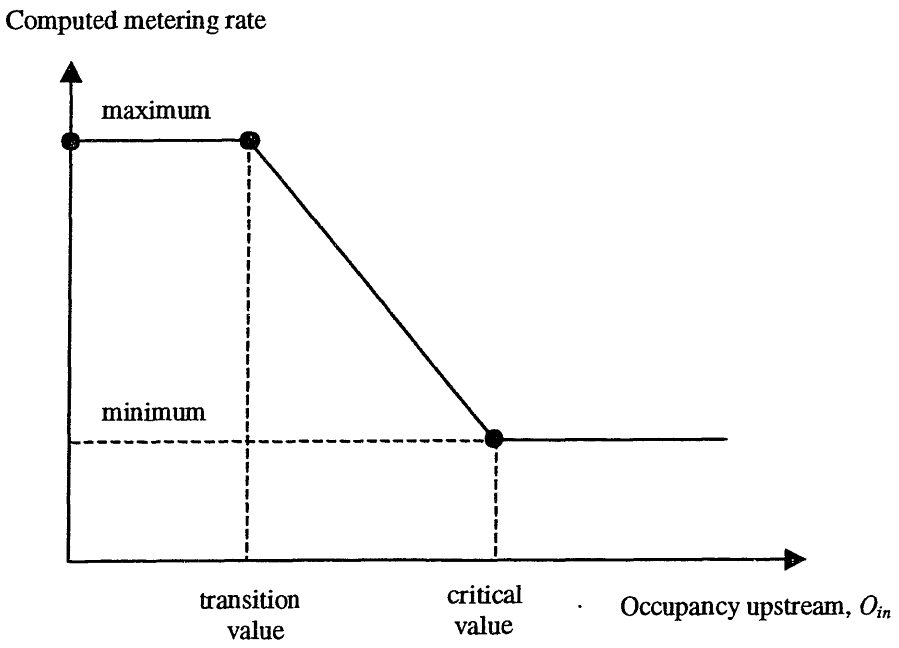

Fig. 2.2. Percent-Occupancy Strategy.

2.1.4 Closed Loop Control

Ramp control systems can also be categorized as open-loop or closed-loop. In an open-loop ramp control system, the control input (for example, metering rate) is independent of the system output i.e. the existing traffic conditions (for example, volume, occupancy etc.). Demand-capacity strategy is an example of typical open-loop ramp control systems. In contrast, the control input is a function of the system output in a closed loop ramp control system. Figure 2.3 illustrates a closed loop ramp control system. In this system, the surveillance devices provide real time traffic data to the ramp controllers. The ramp control plans are then computed based on the surveillance data. The implemented control plan influences the traffic conditions. The controller receives the updated traffic information and the cycle continues.

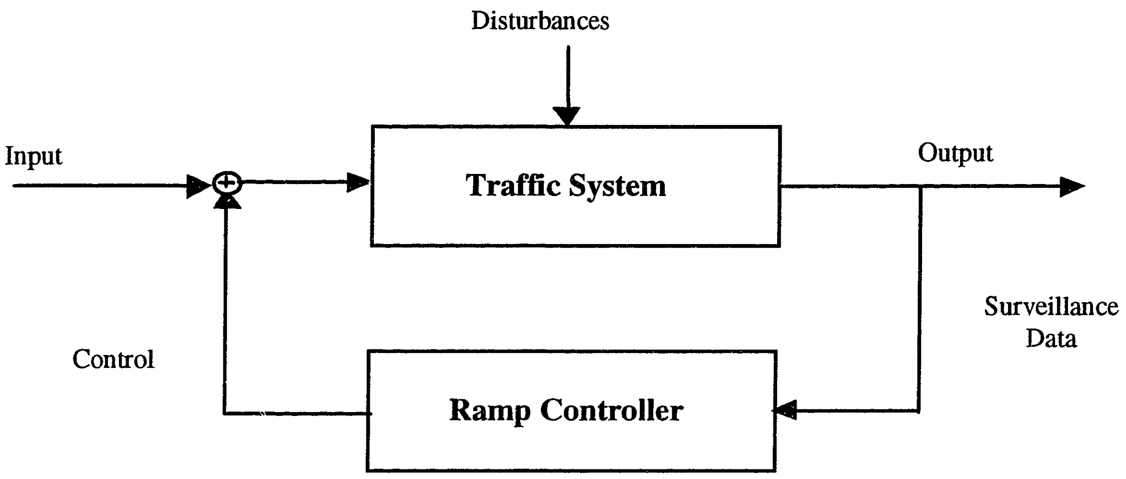

Fig. 2.3. A Closed-Loop Ramp Control System

Closed-loop controls are also known as feedback control. Feedback control methods in traffic control were introduced in the early 70s (Payne, et al., 1973, Isaksen and Payne, 1973). One of the most popular local control strategies is derived from the linear quadratic (LQ) feedback control method. Several ramp control algorithms have been proposed on the basis of this law (Papageorgiou et al., 1991, Zhang et al., 1994).

The LQ (Linear Quadratic) regulator is a linear feedback control law that is based on minimizing a quadratic performance index subject to a system of linear equations which represent the traffic dynamics. In this method, first the dynamic traffic process is represented by the following nonlinear equation -

$$x_{t+1} = f(x_t, u_t) \qquad (2.2)$$

where x_t and u_t are state and control variables at time t respectively. Traffic flow equations are linearized (Equation 2.2) around a set of steady-state conditions, and the control law is obtained as a linear function of observed traffic deviations from the steady-state conditions. The objective of the local feedback control is to minimize the deviations from the steady states (x', u'). It leads to the following feedback control law:

$$u_t = u' - L(x', u')(x_t - x') \qquad (2.3)$$

where $L(x', u')$ is the control gain matrix (see Athans et al., 1975, Papageorgiou et al., 1991 for details). The control law of (2.3) is called a LQ regulator. If there is congestion (i.e. the measured state x_t is higher than the desired value x'), the last term in the right hand side of (2.3) is negative and control variable is decreased relative to the steady-state value. Similarly, if there is no congestion, the control input is increased above the steady-state value. In the context of ramp metering, the control variables in Equation 2.3 are the metering rates and the state variables are traffic measurements (for example occupancy).

2.2 Area-Wide Ramp Control

The area-wide ramp control problem can be broadly divided into three categories based on their formulation. They are – optimal control methods, feedback control methods and heuristic methods. There is another class of control method that uses the combinations of the above three methods and is known as hierarchical control.

2.2.1 Optimal Control

The area-wide optimal ramp control problem was first formulated by Wattleworth and Berry (1965) as a linear programming problem. Since then, many researchers have used optimization techniques for designing efficient ramp control strategies. The problem includes the following three main components: a) A traffic flow model, b) Control variables, and c) A performance index or objective function. Existing area-wide optimal control models can be divided into three categories: static, sequential and dynamic models.

2.2.1.1 Static Control

The static optimal control strategies are derived from historic traffic data, e.g. historic demands. The static control model can produce fixed-time or time-of-day control policies. An early mathematical formulation of the static optimal control problem was proposed by Wattleworth and Berry (1965) and Wattleworth (1967). In this formulation, a freeway corridor is divided into several homogeneous sections in such a way that each section has no more than one on-ramp and one off-ramp. The ramp demand is assumed as known. The problem is to find admissible ramp volumes that maximize a performance index (e.g. sum of input flows or outputs) subject to capacity constraints. Most ramp meters implemented in the United States (either fixed-time or time-of-day) are not traffic responsive and assume a steady-state traffic condition. In those implementations, the vehicle movement or flow propagation over the network is not considered.

2.2.1.2 Sequential Control

The sequential approach overcomes one weakness of static control models by including real time traffic demand and ramp queue information (Isaksen and Payne, 1973, Papageorgiou, 1980 & 1983, and Chang, et al., 1994). The time horizon is divided into a sequence of equal time intervals. The metering rate for each time interval is calculated by the linear programming approach of the static model. Performance index is optimized over all time periods subject to the capacity constraints and ramp queue constraints. The model uses a modified ramp demand in each time interval by adding the on-ramp queue in the previous time period to the current demand. The real time input requirements for this type of approach are - demand at each entry ramp for each time interval and the number of vehicles waiting at each entry ramp for each time period.

2.2.1.3 Dynamic Model

Although sequential models include demand and queuing dynamics, the representation of traffic flow remains static, since in each time period the mainline flow is assumed to be in a steady state condition. Consequently, the flow propagation from one section to the next is ignored. Since frequent state transitions and rapid flow variations are observed in the real life traffic systems, the control strategies determined through steady-state models are of limited use (Stephanedes and Chang, 1993).

To overcome this shortcoming, various dynamic models have been developed that are based on mathematical programming approach (Ritchie, et al., 1995, Stephanedes and Chang, 1993, and Chang, et al., 1994). These dynamic models differ from sequential models in their treatment of mainline traffic flows as they represent the evolution of traffic (or flow propagation) unlike the sequential models. All dynamic models are based on the macroscopic traffic flow model. The basic two equations of a macroscopic traffic flow model are the conservation of flow equation and the flow-density relationship. These two equations together with the kinematic wave propagation theory developed by Lighthill and Whitham (1955) and Richards (1956) constitute a complete dynamic traffic flow model.

A dynamic optimal ramp control problem optimizes the performance index or control objective (e.g., total travel time, total delay, total output volume, total input volume, total travel distance, ramp queue etc.) subject to the dynamic traffic flow model, ramp queue constraints and capacity constraint. The resulting problem can be formulated either as a linear program (Chang, et al., 1994) or a non-linear one (Stephanedes and Chang, 1993), depending on the whether the traffic flow relationship is linearized or not.

2.2.2 Feedback Control

A coordinated feedback control strategy for ramp metering can be derived by the application of linear-quadratic methodology. The control law in this case has multiple variables as opposed to single variable for a local feedback control. Existing theories do not provide theoretical tools for the derivation of multivariable feedback control laws for large-scale nonlinear systems like the freeway traffic system. On the other hand, a powerful tool for designing multivariable feedback control laws for linear systems is the linear quadratic (LQ) optimization theory. With a proper linearization around a desired steady state, this technique can be applied to traffic systems. Similar to the local feedback control, a quadratic performance criterion is used as the objective function to penalize deviations of the problem variables from their steady states. This methodology for deriving coordinated ramp metering strategies was applied by Papageorgiou, et al. (1990).

2.2.3 Hierarchical Control

A typical hierarchical traffic control system (Chen, et al., 1997, Isaksen and Payne, 1973, Athans, et al., 1975, Papageorgiou, 1983, Hotz, et al., 1992) combines both local and area-wide strategies. Chen et al. (1997) used a hierarchical feedback control system for ramp metering which is schematically shown in Figure 2.4.

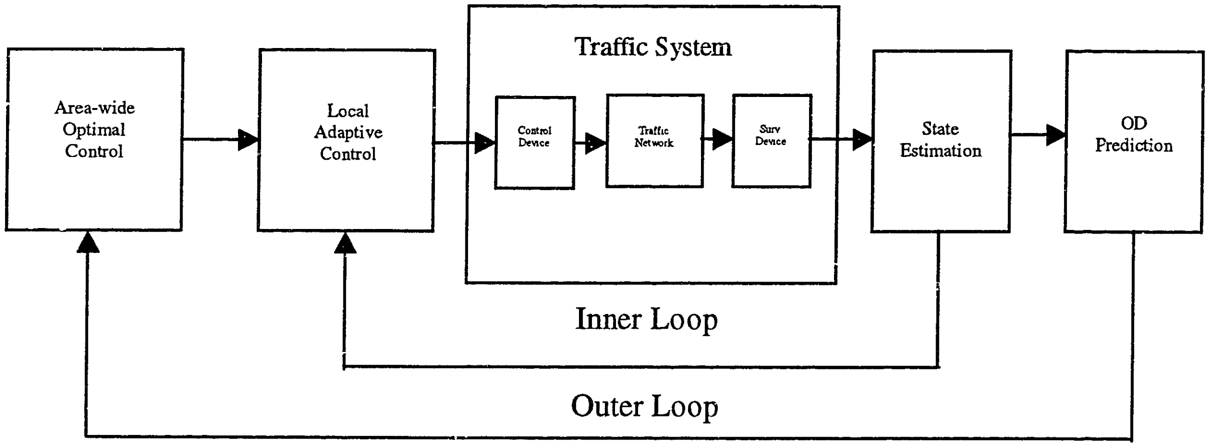

Fig. 2.4. A Hierarchical Feedback System.

The hierarchical feedback system shown in Figure 2.4 has two feedback loops. The inner loop is employed at the local level while an outer loop is used for the area-wide traffic management. This hierarchical system consists of four modules: *state estimation, OD prediction, local control* and *area-wide control.* The state estimation module obtains the best estimates of current network state based on the surveillance data. The OD prediction module takes the input from state estimation and predicts future origin destination demand. Based on estimated state variables and predicted OD demand, the area-wide control module optimizes the control values (metering rate) to obtain a system objective. The distributed local control module then locally adjusts the values set by the area-wide control to compensate for the exogenous disturbances and system errors (such as errors in state estimation and OD prediction). The inner loop is distributed over the network with little or no communication and computation effort while the outer loop is centralized for the entire network with more intensive communications and computational requirement.

2.2.4 Heuristic Approach

Heuristic approaches for ramp metering are usually not based on a theoretical framework. One such approach was adopted to develop FLOW (Jacobson, et al., 1989). FLOW is a real-time, coordinated, traffic-responsive ramp metering algorithm. The algorithm has two components: a local metering rate (LMR) which is based on local conditions, and a bottleneck metering rate (BMR) which is based on system capacity constraints. Predetermined metering rates are selected on the basis of occupancy level upstream of the metered ramp. The local metering rate is obtained from an occupancy-metering rate table that provides the number of vehicles that should be allowed to enter the mainline. Coordinated BMR accounts for the interdependencies among ramps and is calculated based on demand-capacity relationships. The more restrictive of the local and bottleneck metering rate is selected for implementation. The algorithm is simple in its approach but effective in practice. A detailed description of FLOW is provided in Chapter 3.

2.2.5 Summary of Area-Wide of Ramp Controls

The three types of area-wide optimal ramp control models (static, sequential and dynamic) described above have many similarities in the sense that they all use mathematical programming approach to optimize the overall control objective and thus coordination of all on-ramps is considered. The main difference among these models lies in their treatment of traffic flow. In the static model, all traffic flows are assumed to be in steady-state. In the sequential model, the ramp queuing phenomenon is modeled but the mainline traffic flow is still assumed to be in steady-state. In the dynamic model, both mainline and ramp traffic flows are modeled dynamically. Feedback control law has also been applied in the field of area-wide ramp control.

Multivariable control law can be obtained with the help of linear quadratic optimization theory by linearizing the relationship among fundamental traffic variables around desired steady state. Another type of area-wide ramp control is the hierarchical control, which combines both local and network level control. This approach is based on the application of any of the following methods or their combinations - optimal control, feedback control and heuristics. Heuristic methods have also been used to design area-wide ramp control models.

2.3 Ramp Control Evaluations

Despite theoretical advances in the development of ramp metering, their implementations have been slow. Most existing ramp meters in the field today use either fixed control or demand-capacity control (Papageorgiou et al., 1991). There have been a number of evaluation studies of various ramp control methods. The two methods used in the evaluation of ramp control systems are field operational tests and computer simulations. Different simulation studies have been conducted to test various ramp control strategies, most of which are performed under hypothetical networks and traffic demand. Only a few field studies have been undertaken. In the following sections, a brief description of some of the ramp metering evaluations is presented. It should be mentioned here that for all the evaluation studies described below and elsewhere in this thesis, travel time savings are with respect to the no control scenario unless otherwise specified.

2.3.1 Field Operational Tests

Ramp metering application in the Minneapolis-St Paul metro area has resulted in 30% increase in throughput (ITS International, 1997). Peak hour speeds on the freeway have increased from an average of 48km/h to 77km/h. Lanes on metered freeways typically carry 2,200 to 2,400 vehicles per hour per lane. MnDOT claims that ramp metering reduces rear end collisions associated with stop-and-go conditions and side collisions at merge points. The INFORM

(Information for Motorist) evaluation in Long Island, New York used ramp metering, traffic signal control, and route diversion. This system was found to increase speeds by 13% and VMT (Vehicle miles traveled) by 5% (Smith, 1992). Proper and Cheslow (1997) reported speed increases in the range of 16% to 62% and travel times savings up to 48% for North American traffic management centers using ramp metering.

A number of local ramp metering strategies (ALINEA, demand-capacity, percent-occupancy) were applied in the field at a single ramp of Boulevard Peripherique in Paris (Papageorgiou et al., 1997). The evaluation criteria included: Total travel time (TTT) on the mainline, Total waiting time (TWT) at the ramp, Total time spent (TTS = TTT + TWT), Vehicle miles traveled (VMT), Mean speed (MS) and Mean congestion duration (MCD). It was found that the ALINEA strategy lead to a maximum improvement of all evaluation criteria compared to the other strategies. It produced 16% reduction in TTS, 3% increase in VMT, 23% increase in MS and 51% reduction in MCD compared to the no control case. Another field test was conducted at the same ramp where ALINEA and the WJC strategy (similar to demand-capacity strategy) were compared (Papageorgiou et al., 1997). The WJC strategy was developed by the UK Department of Transport. It was found that ALINEA decreased TTS by 7% and increased VMT and MS by 0.4% and 8% respectively, compared to the WJC strategy. The second implementation of ALINEA and a demand-capacity strategy at a single ramp was done at the A10 West Motorway in Amsterdam where ALINEA was found to result in a travel time savings of 6.3% with respect to the demand capacity strategy (Papageorgiou et al., 1997).

ALINEA was applied at multiple on-ramps of the westbound Boulevard Peripherique. The coordinated feedback control algorithm, METALINE was also applied at the same site (Papageorgiou et al., 1997). The field tests showed that ALINEA improved TTS, VMT and MS by 5.2%, 1.4% and 6.8% respectively; the corresponding improvements for METALINE were 4.8%, 0% and 4.8% respectively, compared to the no control case. So, both feedback control strategies lead to roughly the same results. This was perhaps due to the reason that the gradual building up of congestion proceeded slowly enough for local control to adapt to changing traffic conditions in a similar manner as coordinated control.

ALINEA was also used as a component of integrated control in an urban corridor network (Corridor Peripherique in Paris) that included a freeway, a parallel arterial, and connecting radial streets (Papageorgiou, et al., 1997). The impact of ramp metering on corridor traffic was studied by comparative evaluation of several performance indices for with and without control. The main findings of this study was that application of an efficient ramp metering strategy can considerably improve traffic conditions not only on the freeway but also on the parallel arterial and the entire network. ALINEA resulted in improvements of 8.1%, -6.9% and 20% in total time spent for the freeway (including the ramps), the arterial, and the radial streets respectively. The reduction in travel time for the entire network was 5.9%. The benefits were even higher if non-recurrent congestion caused by incidents were included in the evaluation.

An evaluation study was undertaken to determine the effectiveness of a heuristic coordinated algorithm (FLOW) in the Seattle metropolitan area (Jacobson, et al., 1989). The 22 meters on I-5 reduced the waiting time on the metered ramps from an average of 5-8 minutes per vehicle to an average of less than 2 minutes. Since metering began, the travel times have remained fairly stable although mainline volumes during the morning peak have increased 49%. In other words, the mainline travel times improved while traffic demands in the region increased, indicating a better utilization of the capacity. From the pre-metering period (October 1976 through September 1981) to the evaluation period (March 1985 through May 1987), the northbound accident rate during the afternoon peak period dropped form 1.49 to 0.92 accidents per million vehicle-miles. The southbound accident rate, during the morning peak period, dropped from 1.31 to 0.79 per million vehicle-miles. Although there might be other factors contributing to a reduction in the accident rate, it appeared that the metering system is a significant cause of the reduced accident rates.

2.3.2 Simulation Based Evaluations

Although field operational tests are ideal for the evaluation of any traffic control system, they tend to be prohibitively expensive, time consuming, and sometimes infeasible. In addition, the test results depend on uncontrollable elements (e.g. weather conditions, travel demand, incidents) and an accurate analysis of the impacts of ramp control is often not possible due to confounding effects. In recent years, simulation has emerged as an alternate tool to evaluate the performance of traffic controls and to select an appropriate design. Simulation studies can also be used to analyze the robustness of a design by evaluating a range of scenarios, and to calibrate control parameters. A number of studies have simulated ramp metering for different transportation networks.

Hellinga and Van Aerde, (1995), used INTEGRATION, a macroscopic traffic simulator, to evaluate a time-of-day ramp control for a test network, and found a slight reduction (0.39%) in total network travel time. Based on a sensitivity analysis, they discovered that the traffic conditions were influenced by the timing of ramp metering implementations, suggesting benefit from metering strategies that use real-time traffic data. The CORSIM (CORridor SIMulation) microscopic simulator was used for the evaluation of time-of-day, fixed time metering in the Atlanta metropolitan area (Matson, et al., 1998). Before and after travel times for the I-75 northbound corridor indicated a 16.5% decrease in total travel time and a 19.7% increase in average speed for the freeway sections. Papageorgiou (1980) used a dynamic traffic model to simulate time-of-day ramp control. The model takes into account the time delay of a volume change at a ramp and its impact at downstream locations. For a hypothetical freeway traffic situation, travel time improvements of 24% and 14% with respect to the case of earlier time-of-day control procedures were reported. A dynamic traffic model was used by Papageorgiou (1983) to study the efficiency of a hierarchical ramp control system. He simulated the no control and the hierarchical control case on a hypothetical freeway stretch and showed the improvements by the hierarchical control.

The local feedback control algorithm (ALINEA) and the coordinated feedback control algorithm (METALINE) were tested in simulation studies by Papageorgiou et el. (1990 & 1991). They simulated these algorithms for the Boulevard Peripherique in Paris using METANET macroscopic traffic simulator. Both feedback control strategies were found to decrease the total travel time (they led to roughly the same results under normal conditions) with METALINE resulting in slightly better performance for non-recurrent congestion. During non-recurrent congestion, bottlenecks may form at unexpected locations which may be better identified and incorporated by a coordinated algorithm. The Statistical Traffic Model (STM) simulation (Whittaker et al., 1997) was used to test the NMSS feedback control (a multivariable feedback control law) algorithm for the A10 West Motorway in Amsterdam (Young et al., 1994). Simulation results showed that the multivariable control algorithm was able to prevent the congestion that was otherwise present in an identical no control scenario. A simulation test of optimal ramp metering control with the TRAF simulation software in the I-94 freeway corridor in St Paul, Minneapolis showed travel time reductions (Stephanedes, et al., 1993). Ritchie et al. (1995) used INTRAS (INtegrated TRAffic Simulation) microscopic traffic simulator to empirically validate theoretical results of an area-wide optimal ramp control strategy for a stretch of freeway in Pasadena, California. Five different predetermined metering rates were used for the simulation. This non traffic responsive, fixed time control strategy had little impact on the mainline, but potentially negative impacts on ramps and surface streets. Another simulation study of an integrated control system was performed by Gardes et al. (1993), investigating ATIS and ATMS control for the Smart Corridor in Los Angeles. Three types of ATMS/ATIS controls were used: ramp metering, traffic signal control, and route diversion. A no control case and five combinations of controls were simulated for the base condition using the INTEGRATION macroscopic model. The results showed marginal travel time improvements.

Chen et al. (1997), used MITSIM microscopic traffic simulator to test three control algorithms - local control, area control and bilevel control that combined both local and area controls. The network used was the Central Artery/Tunnel (CA/T) network in Boston. The study showed that the bilevel control outperformed other control strategies. The improvements in total throughput for the local, area-wide, and bilevel controls were 4.9%, 5.1% and 8.4% respectively. The travel time savings for the three control strategies were 9.4%, 8.8% and 12.6% respectively.

2.4 Observations

Based on the literature review presented in this chapter, we have seen that there have been significant theoretical developments in the area of ramp metering. Various studies have been undertaken to evaluate the performance of different ramp control models. Scope of these evaluation studies is limited as they do not consider the effect of a wide range of traffic variables (e.g. traffic demands, downstream condition, queue override strategies) that may have significant impact on the performance of any ramp control model. These effects should be evaluated using systematic experimental designs which are also lacking in the existing studies. Besides, many of these evaluation studies were performed using macroscopic simulators which may not be adequate for such evaluations as a result of their coarse representation of traffic flow. This may suggest the use of microscopic simulations because of the more accurate modeling of merging behavior. Therefore, it can be concluded that there is a need for such studies that identify these variables and systematically quantify their effects on the ramp control models with proper simulation technique. This might lead to a better understanding of the applicability and effectiveness of different ramp metering approaches over a wide range of values for these variables. The motivation to undertake the evaluation study presented in this thesis was derived from the above observations.

In the next chapter, the evaluation framework used for this research will be presented in details.

Chapter 3

Evaluation Framework

Evaluation of ramp metering algorithms with MITSIM laboratory is carried out to check their performance and test the sensitivity with respect to key variables. Evaluation also helps identify the shortcomings of the algorithms and the conditions under which the algorithms do not perform satisfactorily. The evaluation study comprises of two stages: The first stage presents the calibration of input parameters in order to obtain algorithms' best performance for the network under consideration. The second stage performs a comparative study of the algorithms with respect to key inputs, described in details in the following sections. An orthogonal fractional factorial design is selected to reduce the number of experiments. The purpose of the design is to systematically evaluate and compare the effects of the experimental factors on the performance of the algorithms. It should be mentioned here that the values of the calibrated input parameters obtained from the first stage of the study are used for the experimental scenarios in the second stage. This chapter describes the MITSIM laboratory, the algorithms used for evaluation, the calibration of the input parameters and the experimental design.

3.1 MITSIM Laboratory

The evaluation study is performed using a microscopic traffic simulation laboratory called MITSIM Laboratory. The laboratory has two components: a MIcroscopic Traffic SIMulator (MITSIM) and a Traffic Management Simulator (TMS). MITSIM is responsible for generating vehicles and simulating their movements in the network. The vehicle movements are based on their desired speeds, lane changing and car following behavior, and responses to control. MITSIM also simulates the road network and the surveillance system. The core of the simulation laboratory is the dynamic interaction between individual vehicles with other vehicles and traffic control. Besides, the graphical interface of MITSIM laboratory offers the added advantage by providing animation of vehicles. This can provide additional insights into the impact of ramp metering. A brief description of the two components of MITSIM laboratory is given in the next sections. Further information about MITSIM laboratory can be found in Ben-Akiva et. al. (1997).

3.1.1 MIcroscopic Traffic SIMulator (MITSIM)

The main elements of MITSIM and their characteristics are outlined below.

Network Components The road network consists of nodes, links, segments, and lanes. The surveillance system consists of various detectors that collect traffic data including volume, speed, occupancy etc. Traffic control devices (e.g. ramp meters) are also represented. Their states are dynamically updated by the traffic management simulator.

Travel Demand The traffic simulator accepts time dependent origin to destination (OD) tables as input.

Vehicle Movement and Driving Behavior The OD tables specified in a scenario are translated into individual vehicle. Behavioral parameters (e.g. desired speed, aggressiveness, critical gaps for changing lane, compliance rates to control devices etc.), information accessibility, and vehicle characteristic parameters (e.g. size, acceleration/deceleration capabilities etc.) are assigned to each vehicle/driver combination based on input distribution. The simulator moves vehicles according to car-following and lane-changing models. MITSIM models drivers' responses to traffic control devices. Vehicles are moved at a fixed step size along their paths in accordance with various constraints.

3.1.2 Traffic Management Simulator (TMS)

TMS is responsible for simulating the operations of a traffic management center. It uses real-time traffic measurements as input from the surveillance systems in MITSIM. Based on the surveillance data, TMS generates control and route guidance according to the implemented logic and updates the states of traffic control devices in the network. For example, a ramp metering algorithm may use occupancy data from the sensors to determine the metering rate, which is implemented in MITSIM.

3.2 Algorithms Evaluated

As mentioned before, the algorithms used for this evaluation study are a local feedback control algorithm ALINEA, and an area-wide heuristic algorithm FLOW. These algorithms were selected on the basis of their traffic responsiveness, demonstration of their previous applications and simplicity. ALINEA is a representative of local control algorithms and FLOW is a representative of the heuristic coordinated algorithms. Both algorithms use real time traffic surveillance data as input. The algorithms are briefly described in the following sections.

3.2.1 ALINEA

ALINEA is a local ramp control algorithm that is based on a feedback principle. The basic idea is to maintain an optimal occupancy on the mainline that will maximize the throughput. The closed loop feedback control strategy for ALINEA can be illustrated with the help of Figure 3.1.

As shown in Figure 3.1, the control law of ALINEA can be stated (see Papageorgiou et. al., 1989) as :

$$r(k) = r(k-1) + K_R\left[o - o_{out}(k)\right] \tag{3.1}$$

where o is the desired occupancy, $o_{out}(k)$is the measured occupancy in the mainline section during time interval k, $r(k)$ is the metering rate for time interval k, and K_R is a regulator parameter. In field experiments, it was found that ALINEA is not very sensitive with respect to K_R. Therefore, we used the K_R value (70 veh/hr) as recommended by Papageorgiou et al. (1990).

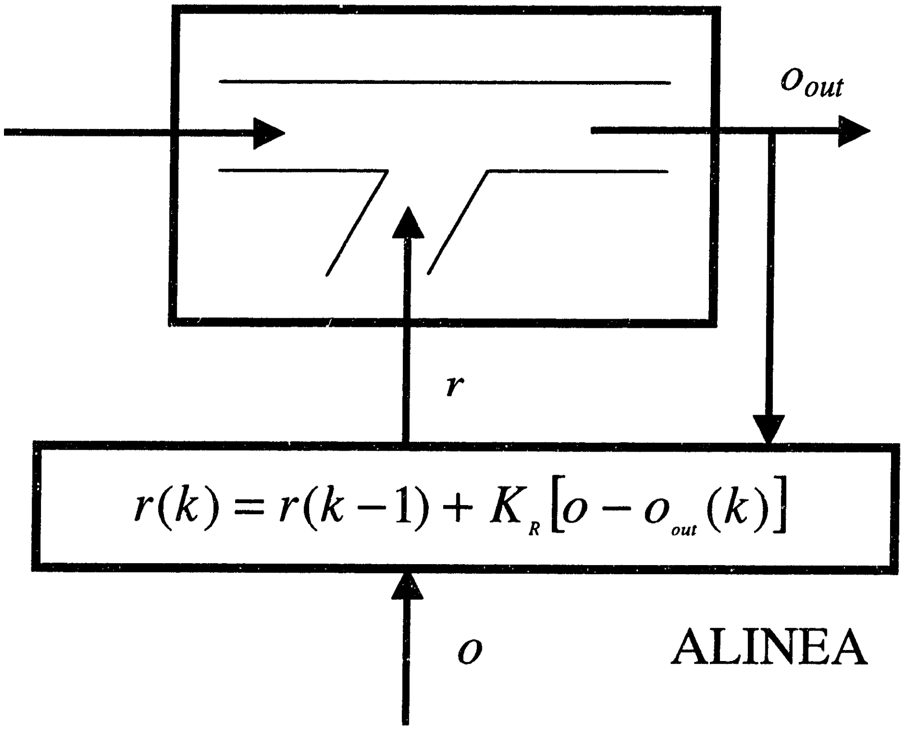

Fig 3.1. ALINEA Feedback Control Strategy

This feedback law is simpler than other local metering strategies. If the measured occupancy $o_{out}(k)$ at cycle k is found to be lower (higher) than the desired occupancy o, the term $o-o_{out}(k)$ of the right hand side of equation 3.1 becomes positive (negative) and the ordered on-ramp volume $r(k)$ is increased (decreased) as compared to its last value $r(k-1)$. Since, the feedback law acts in the same way for both congested and light traffic, no switchings are necessary. The algorithm has been found (Papageorgiou et al., 1997) to react smoothly for small values of "o - $o_{out}(k)$" and to stabilize traffic flow at a higher throughput level.

ALINEA requires only one detector station in the desired location where occupancy o_{out} is measured. The location should be such that the congestion due to on-ramp volumes should be visible in the measurements. Regardless of the upstream traffic volume, the feedback law in ALINEA attempts to obtain desired occupancy. The input parameters for ALINEA are the desired occupancy (o in equation 3.1) and the mainline detector location where the desired occupancy is maintained.

The main reason for regulating occupancy, rather than volume, is that traffic volume may have the same values for both light and congested traffic (Fig 1.1). An additional advantage is that the critical occupancy o_{cr} seems to be less sensitive with respect to exogenous variables (e.g. weather conditions) than the capacity flow. Excessive queue lengths may be detected by suitably placing detectors on the ramp and heuristically accounting for that in the metering rate.

3.2.2 FLOW

In response to growing freeway congestion problems in the Seattle area, the Washington State Department of Transportation (WSDOT) initiated a ramp control program in 1981. The ramp control system is a part of a region-wide transportation system management effort called FLOW. It is an integrated, traffic-responsive metering algorithm in which metering rates are calculated in real time based on system as well as local capacity conditions. In addition, queuing conditions on the ramps are also considered in the final calculation of metering rates. The metering algorithm has three components: calculation of metering rates based on local conditions, calculation of metering rates based on system capacity constraints, and adjustment to the metering rates based on queue lengths on the ramps. A generalized flow diagram of the algorithm is presented in Figure 3.2.

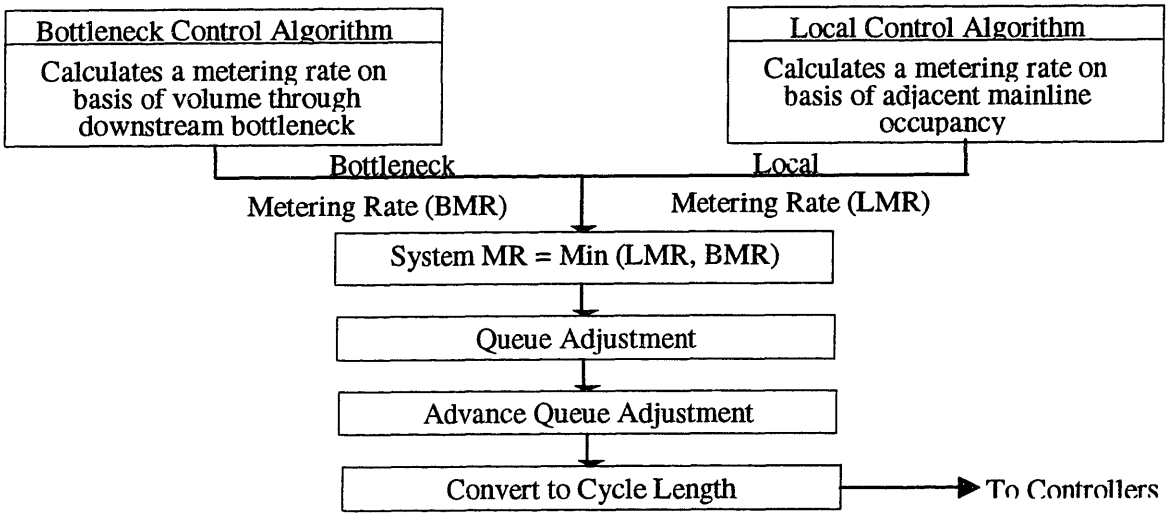

Fig 3.2. FLOW Ramp Metering Algorithm

Local Metering Rate One widely used method for calculating metering rates based on local conditions is traffic-responsive metering using occupancy data. Predetermined metering rates are selected on the basis of occupancy level upstream of the given metered ramp. Historical data are collected from the given location and are used to determine approximate volume-occupancy relationship. Based on volume-occupancy relationship, a look-up table is developed for each metered ramp that provides the metering rate for a given occupancy level. The metering rate is basically equal to the difference between volume and capacity.

System, or Bottleneck, Metering Rate One significant aspect of FLOW is the calculation of metering rates on the basis of system capacity constraints. A coordinated ramp control system is distinguished from a local control by the application of ramp control to a series of entrance ramps where the interdependencies among entrance ramps is taken into account. System-wide conditions and capacity constraints drive the calculation of metering rates at all metered ramps in the system. The resulting metering rate is then subject to adjustment on the basis of ramp queues, minimum metering rate, and potentially other conditions.

The entire freeway is divided into several sections for the calculation of bottleneck metering rate (BMR). A freeway section is defined by a stretch of the road between two mainline detector stations. If the downstream detector station detects an occupancy above a threshold, then the section is said to be operating near capacity. If the section is operating near capacity and the total volume entering the section exceeds the total volume exiting the section, then the section is said to be storing vehicles. In any generalized freeway section i such as the one depicted in Figure 3.3, these conditions for any time period t can be described as follows:

1. Capacity Condition

$$o \geq o_{th}, \tag{3.2}$$

where

o = average occupancy at the downstream detector, and

o_{th} = the occupancy threshold for the downstream detector station.

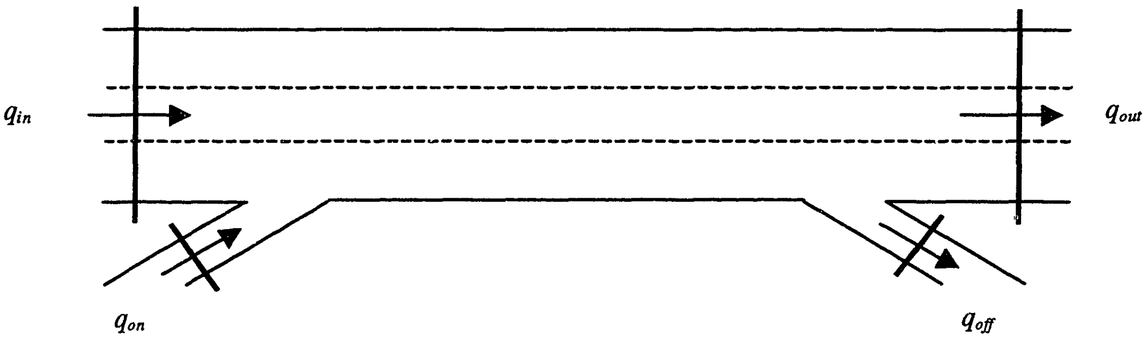

Fig. 3.3. A Generalized Freeway Section

2. Vehicle Storage Condition

$$q_{in} + q_{on} \geq q_{out} + q_{off} \tag{3.3}$$

where

q_{in} = inflow from mainline,

q_{on} = inflow from on-ramp,

q_{out} = outflow to mainline, and

q_{off} = outflow to off-ramp.

If conditions 3.2 and 3.3 are met, the system calculates the upstream ramp volume reduction as the number of vehicles being stored in the freeway section during the said time period t. This value becomes the total by which upstream ramp volumes must be reduced. The upstream ramp volume reduction is calculated as

$$U_i = (q_{in} + q_{on}) - (q_{out} + q_{off}) \tag{3.4}$$

where U_i = upstream ramp volume reduction for section i to be implemented in the next interval.

Based on historical data and field experience, a control area consisting of several on and off ramps is identified for each freeway section. The control area is defined based on the location of potential bottlenecks in the network. It is assumed that the congestion in a freeway section can be mitigated by controlling entering traffic in the corresponding control area. This control area is called influence zone. Thus, at least one influence zone is assigned to each freeway section in the network and the total volume reduction for a section is distributed among the upstream ramps in the influence zone on the basis of a set of weighting factors. Each metered ramp in the system is assigned a weighting factor according to its distance from the downstream boundary of the influence zone and the average demand level on the ramp. The value of weighting factor usually increases with decrease in distance between on-ramp and the downstream boundary of the influence zone because vehicles using these ramps are more likely to go through the bottleneck.

The bottleneck metering rate reduction (BMRR) for on-ramps in section *i* is given by

$$BMRR_{j(t+1)} = U_t \times \frac{WF_j}{\sum_j^n (WF_j)} \tag{3.5}$$

where

$BMRR_{j(t+1)}$ = bottleneck metering rate reduction for ramp *j* for the time interval *(t+1)*,

U_t = upstream ramp volume reduction calculated at time interval *t*,

WF_j = weighting factor for ramp *j*, and

n = number of ramps in the influence zone.

The system calculates the bottleneck metering rate for each ramp by subtracting the bottleneck metering rate reduction from the ramp's volume during the last interval. The calculation becomes

$$BMR_{j(t+1)} = q_{on_{jt}} - BMRR_{j(t+1)} \tag{3.6}$$

where

$BMR_{j(t+1)}$ = bottleneck metering rate for ramp *j* for the time interval *(t+1)*,

$q_{on_{jt}}$ = measured volume on ramp *j* during time interval *t*.

Areas of influence may overlap; therefore, any given ramp may have several bottleneck metering rates. The most restrictive of these rates is selected as the final bottleneck metering rate for that ramp.

Adjustments to the Calculated Metering Rate After both the local and the bottleneck metering rates are calculated for a given ramp, the system selects the more restrictive of the two as System

Metering Rate (SMR). Then, SMR is subject to two further adjustments called queue adjustment and advance queue adjustment.

Two queue detectors are needed on on-ramps for adjustment purposes. The adjustments are implemented primarily to avoid an unacceptable delay for on-ramp vehicles and subsequent interference of ramp traffic with urban roads. One queue detector is placed at a point such that any spillback beyond this point is unacceptable. The other detector is placed downstream of the first one. If ramp queue reaches the second detector (downstream location), SMR is slightly increased to reduce excessive delay to the ramp traffic. This increase is known as queue override. If ramp queue reaches the first detector (upstream location), SMR is increased further to avoid any operational difficulties. This increase is known as advance queue override. For this study, value of queue override is 3 additional vehicles per minute; advance queue override requires ramp metering to be suspended when the queue reaches upstream queue detector.

The algorithm is well suited to real-time control and capacities do not have to be calculated off-line. Control strategies and metering plans do not have to be updated. The system automatically adjusts for incidents and weather conditions. When an incident occurs, the system operates under the same algorithm but reacts to the reduced capacity caused by the incident. Also, relatively few parameters need to be monitored.

3.3 Application to the Central Artery/Tunnel Project

A part of the Central Artery/Tunnel (CA/T) Project in Boston is used as the test network (Figure 3.5) for this evaluation study. The project will replace the existing Central Artery (I-93) and connect the Massachusetts Turnpike (I-90) to Logan International Airport. It is a 7.5 mile Interstate highway, approximately half of which will be built as a tunnel. The tunnel design makes the CA/T network unique and poses a number of challenges to drivers and designers of the network. The network is expected to carry a large demand of 250,000 daily trips through the Central Artery and 100,000 daily trips through the Ted Williams Tunnel by the year 2010.

3.4 Experimental Setup

MITSIM is a stochastic simulator and as a result, outputs from MITSIM are also stochastic. Therefore, each experiment had to be run multiple times in order to get statistically significant results. It was found that fifteen replications of each experiment produced results with error percentages within acceptable limits. Errors associated with origin-destination travel times varied from 0.5% to 6% (increasing with increasing demand). The lowest error percentage – 0.5% was associated with 80% OD demand level, whereas the highest error percentage – 6% was associated with 120% demand. OD travel times were collected for vehicles which departed between minutes 15 and 30. Simulation experiments were performed for a sufficient duration so that all vehicles departing between minutes 15 and 30 reached their destinations. The total number of scenarios that were tested for this study is 100. 15 Replications were used for each scenario. Thus, the total number of replications performed was 1500, consuming approximately 5000 computer hours.

3.4.1 Test Network

Interstate-93 North of the CA/T Project in Boston is used as the test network for this evaluation study. The network is expected to experience a high traffic demand beginning from the year 2004 when it is expected to be operational. Projected evening peak hourly volumes for 2004 are shown in Figure 3.4.

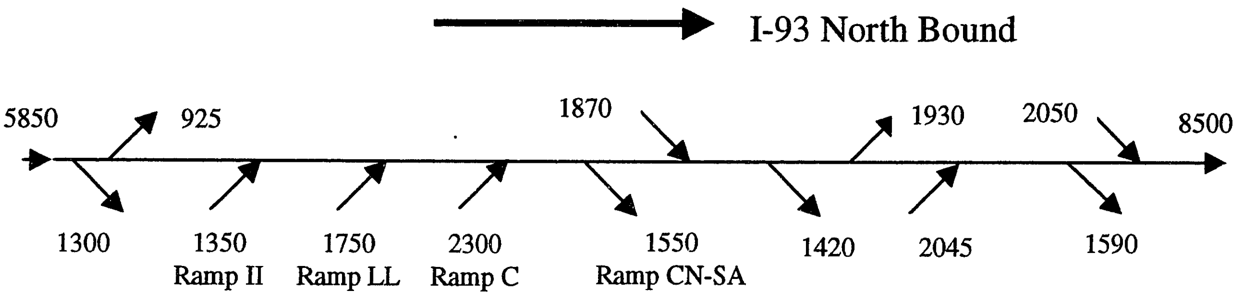

Fig 3.4. Hourly Volume Level for I-93 North-Bound

The number of on and off-ramps in this network are six and five respectively. However, only three on-ramps –Ramp II, Ramp LL, and Ramp C, are meterable. It should be mentioned that the CA/T project terminology for on and off-ramps is used throughout this thesis. The locations of these on-ramps in the CA/T network are shown in Figure 3.5. The on-ramps that are not metered are located downstream of Ramp CN-SA (Figure 3.4). Ramp II and Ramp LL consist of acceleration lanes of approximately 150 ft length, while Ramp C merges with the mainline as an add lane. Figure 3.6 presents lane-level geometry of the network.

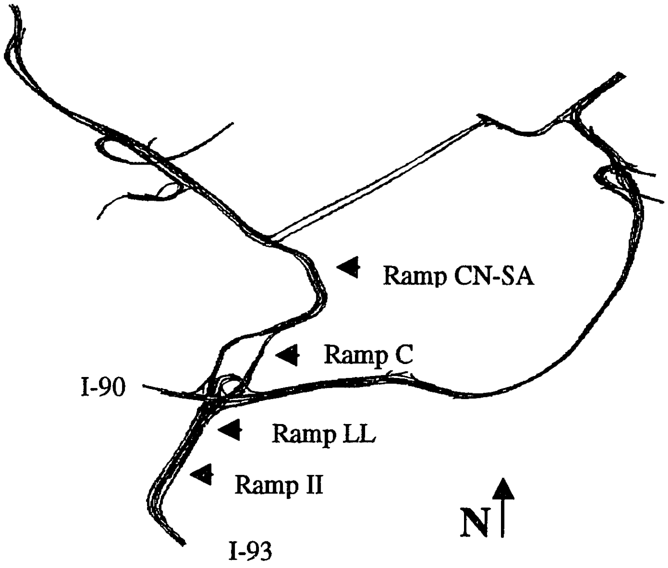

Fig 3.5. Locations of the Ramps used for Metering in the CA/T Network

3.4.2 Calibration of Input Parameters

A brief description of the input parameters for ALINEA and FLOW that are used for calibration will be presented in this section. The calibration results will be presented in the next chapter.

3.4.2.1 Input Parameters for ALINEA

ALINEA attempts to maximize the mainline throughput by maintaining an optimal occupancy, called target occupancy. Conceptually, target occupancy should be maintained at a location where congestion due to merging traffic is first visible. Thus there are two key parameters for the implementation of ALINEA: the target occupancy value, and the location of mainline detector where target occupancy should be maintained. A brief description of these input parameters is given below.

Target Occupancy The performance of the algorithm depends on the value used as target occupancy. Flow-occupancy diagrams for different sections, obtained from preliminary investigations, suggested a critical occupancy value in the vicinity of 20%. Therefore, we decided to use four levels of target occupancy: 15%, 19%, 21%, and 23%, for calibration.

Mainline Detector Location The target occupancy should be maintained at a location such that mainline congestion can most quickly and easily be identified in the best possible manner. Preliminary simulations indicated that Ramp LL is the most critical ramp to be metered because of the congestion created downstream of this ramp. Further consideration of the network geometry revealed that the performance of ALINEA would be sensitive to detector location for this ramp. It is important to observe that the length of the acceleration lane for Ramp LL is very short and the demand is very high, giving rise to a complex merging pattern. Therefore, we evaluate the performance of three mainline detector locations downstream of Ramp LL to identify the most critical location to maintain target occupancy and select the best location for the second stage of this study. Ramp C merges as an add lane and therefore, does not represent a potential case for studying the impact of detector location. Although Ramp II has a similar geometry to Ramp LL, the hourly volume on Ramp II is relatively low and the congestion from this ramp is not critical. As a result, only one detector location on mainline for each of these ramps is considered.

The three detector locations for Ramp LL are:- approximately 30 ft upstream of the acceleration lane drop (location L1 in Figure 3.6), approximately 40 ft downstream of the acceleration lane drop (location L2 in Figure 3.6), and approximately 300 ft downstream of the acceleration lane drop (location L3 in Figure 3.6). For Ramp II, the detector location is approximately 35 ft upstream of the acceleration lane drop; whereas, for Ramp C, it is approximately 40 ft downstream of the merge area.

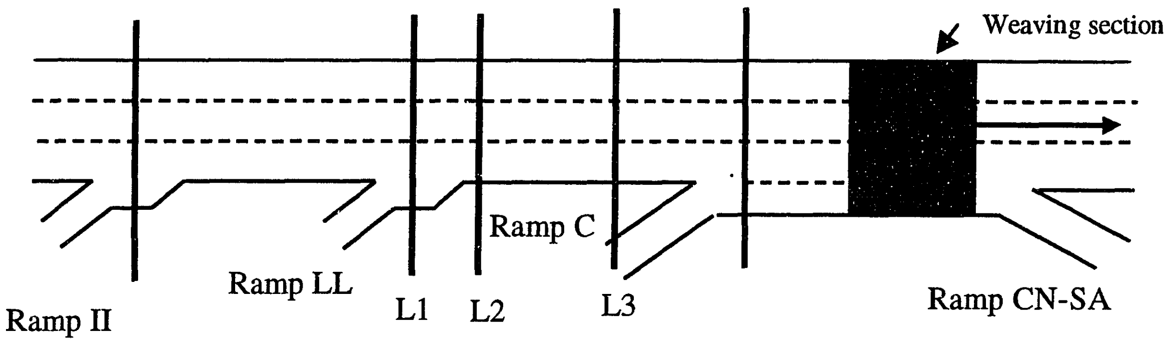

Fig. 3.6. Mainline Detector Locations for the Metered Ramps

3.4.2.2 Input Parameters for FLOW

Influence zone configurations are found to be highly sensitive to network geometry and demand pattern (Jacobson et al. 1989) and therefore, we decided to calibrate this parameter for the CA/T network. Two influence zones are evaluated for this purpose.

Influence Zone Preliminary simulations were conducted to identify the sections where vehicle storage was likely to take place. Based on these results, two influence zones were selected for calibration. The locations of the influence zones in the test network are shown in Figure 3.7. For influence zone 1, the weighting factors for Ramp C, Ramp LL and Ramp II are 0.5, 0.3, and 0.2 respectively, whereas, those for Ramp C and Ramp LL for influence zone 2 are 0.6 and 0.4 respectively. The weighting factor for an on-ramp is selected based on the distance of that ramp

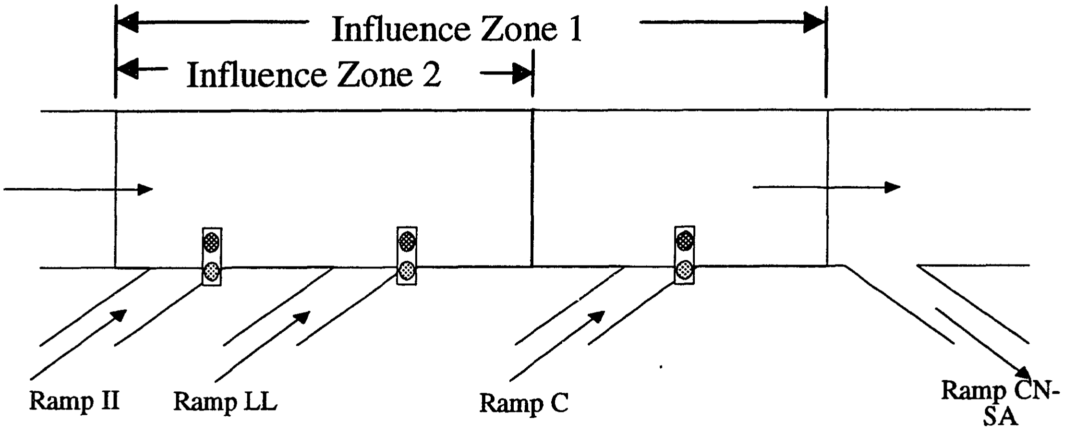

Fig. 3.7. Locations of Influence Zone 1 & 2

from the downstream boundary of the influence zone and the relative traffic volume of the ramp with respect to other on-ramps within the influence zone.

3.4.3 Experimental Design

3.4.3.1 Experimental Factors

Three variables are used in designing experiments for the evaluation of ALINEA and FLOW. They are – Origin Destination (OD) demand, downstream traffic condition, and queue override strategy. These variables are discussed in details in the following subsections.

Traffic Demand Traffic demand is typically specified in the form of origin-destination (OD) matrices, which vary depending on the time of day and vehicle class. Demand for transportation systems are typically determined for the peak and off-peak periods. The demand for a scenario can be specified as a fraction of the peak or off-peak period demand. For example, a 50% of the PM peak period demand level represents 50% of the number of trips for the PM peak. The projected PM peak OD demand for the year 2004 is used as the base demand for this research. Five levels of OD demand – 80%, 90%, 100%, 110%, and 120% of the base demand are used for the evaluation. The time dependent variation in demand within the peak hour is assumed as given in Figure 3.8.

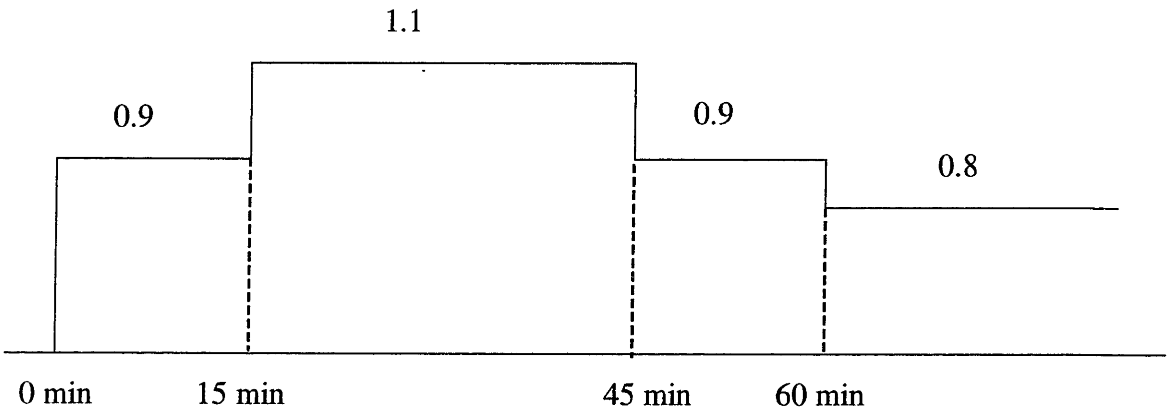

Fig.3.8.Hourly Variations in OD Demand

Downstream Bottleneck Scenario An ideal implementation of a local feedback control algorithm assumes no downstream bottleneck. But this is seldom the case in the real world. So, we evaluate the performance of ALINEA in the presence and absence of a downstream bottleneck. To compare the performance of FLOW and ALINEA under these downstream conditions, FLOW is also evaluated with respect to these two conditions. The two downstream bottleneck conditions are termed as "Condition 1" (presence of downstream bottleneck) and "Condition 2" (absence of downstream bottleneck).

There is a weaving section in the network between Ramp C and Ramp CN-SA (Figure 3.6). As a result of a large number of lane changings in this area, a bottleneck usually forms upstream of Ramp CN-SA. The performance of ALINEA and FLOW is evaluated with respect to two downstream bottleneck conditions. "Condition 1" is simulated by not metering the downstream ramp C and "Condition 2" is simulated by metering Ramp C.

Queue Override Strategy It is believed that the strategy, based on which the queue override (disabling the meter) action on the ramp is implemented, may have an impact on the performance of the algorithm; though its effect has not been tested before. In this research, this effect is studied by varying the position of ramp queue detector(s). . Four queue override strategies are used. One of them is not using any queue override. In this hypothetical case, the ramp queue is allowed to build up infinitely and metering is never suspended. In the other three cases, 100%, 75% and 62.5% of the physical ramp length are used for queue override. For example, in the 75% case, metering is suspended when the ramp queue occupies 75% of the physical ramp length.

3.4.3.2 Factorial Design

For the experimental factors and their levels discussed earlier, the number of scenarios for a full factorial design for each algorithm is equal to (5 levels of OD demand) * (2 downstream bottleneck conditions) * (4 queue override strategies) = 40. Thus, the number of replications for the two algorithms would be 2*15*40 = 1200. Considering the computational requirements, it is not practical to use the full factorial design for this evaluation study. Therefore, we decide to use a fractional factorial experimental plan.

A half orthogonal fraction is selected for our study. This is done to reduce the number of simulations to a feasible number and at the same time retain all the effects of the experimental factors on the algorithms. An orthogonal plan is selected because it permits the estimation of all relevant effects with no correlation and it is also simple to analyze (For detailed information about experimental design, see reference). The experimental design chosen for this study is shown in Table 3.1.

OD Demand : 80% =1
90% =2
100% =3
110% =4
120% =5

Queue Override: No Override =1
100% =2
75% =3
62.5% =4

D/S Condition: With D/S Bottleneck (Condition 1) =1
Without D/S Bottleneck (Condition 2) =2

Scenario	OD Demand	D/S Condition	Queue Override
1	1	1	1
2	1	2	2
3	1	2	3
4	1	1	4
5	2	2	1
6	2	1	2
7	2	1	3
8	2	2	4
9	3	1	1
10	3	2	2
11	3	2	3
12	3	1	4
13	4	2	1
14	4	1	2
15	4	1	3
16	4	2	4
17	5	1	1
18	5	2	2
19	5	2	3
20	5	1	4

Table 3.1. Fractional Experimental Plan

3.4.4 Measures of Effectiveness

The measures of effectiveness (MOEs) used to evaluate the performance of different ramp control algorithms are:

Total System Travel Time This measure considers the total amount of time experienced by all vehicles in the network. Thus, it is a good measure to evaluate system performance for the entire network.

OD Travel Time This MOE considers travel time for vehicles between specific OD pairs. We selected OD travel time as one of the MOEs in order to find the distribution of travel time savings/delays across OD pairs. This measure can be used to consider the effect of control on certain groups of vehicles. For instance, it can consider a group which includes all vehicles that originate from a metered ramp and can demonstrate the impact of ramp metering on ramp vehicles only.

In the next chapter, the results of the calibration of input parameters for FLOW and ALINEA will be presented followed by the results of the comparison study based on the experimental design.

Chapter 4

Simulation Results

In Chapter 3, key input parameters for the algorithms ALINEA and FLOW were selected for calibration in the first stage of our evaluation study. This was done to use the calibrated parameters in the second stage. This chapter will present results for two stage evaluation i.e. calibration and comparison of the algorithms using fractional experiments.

4.1 Calibration Results

The calibration results are presented in Tables 4.1 through 4.8. These tables present the percent travel time savings[1] for different scenarios for ramps and mainline vehicles departing from their origins between minutes 15 and 30. A positive or a negative sign associated with percent travel time savings indicates travel time reduction and increase respectively. Calibration results for ALINEA and FLOW are presented in the following sections.

4.1.1 Calibration Results for ALINEA

The input parameters of ALINEA selected for calibration are target occupancy and mainline detector locations. Results of the calibration of target occupancy are presented first followed by those of mainline detector locations. Three traffic demand levels - 80%, 90%, 100% of the base demand (the year 2004 PM peak OD demand) were used in the calibration of input parameters for ALINEA.

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[1] Throughout this thesis, unless otherwise specified, travel time savings are always reported as savings compared to the no control case.

4.1.1.1 Target occupancy

The calibration results for target occupancy are presented in Table 4.1 through Table 4.3. Table 4.1 presents reduction in travel time for 80% demand. Clearly, there was no improvement from ramp metering at this demand level. The demand seems to be too low to warrant ramp metering. It should be pointed out that 21% occupancy level was not tried for this demand level, because it is believed that it would not provide any further insight for such a low level of demand. It was concluded that a target occupancy value of 15% caused considerable deterioration in system performance, and did not represent a potential candidate in further experiments.

Table 4.1. Percent Travel Time Savings for 80% Demand
(Calibration of target occupancy for ALINEA)

Detector Location	*Occupancy*	*Mainline*	*Ramps*	*Total*
L1	23%	-0.2	-4.3	-2.6
	19%	0.2	-0.2	0.0
	15%	0.3	-17.7	-10.1
L2	23%	0.5	-1.4	-0.6
	19%	0.2	-0.5	-0.2
	15%	0.5	-15.6	-8.8
L3	23%	0.2	-0.5	-0.3
	19%	-0.1	-0.2	-0.2
	15%	1.8	-13.4	-7.0

Table 4.2 illustrates the results for the calibration of target occupancy for 90% demand. It is clear that ALINEA performed best for the target occupancy value of 19%. For this occupancy level, the percentage travel time savings were the largest. Similar results are illustrated in Table 4.3 for OD demand level of 100% where 19% target occupancy outperformed other occupancy levels for all the detector locations. It should be noted that although system travel time increased for all occupancy levels at 80% demand, 19% target occupancy caused the minimum additional delay. Thus, it is evident that 19% occupancy produced best performances of ALINEA. Therefore, it was decided to use the target occupancy value of 19% for further simulation experiments.

Table 4.2. Percent Travel Time Savings for 90% Demand
(Calibration of target occupancy for ALINEA)

Detector Location	***Scenario***	***Mainline***	***Ramps***	***Total***
L1	15%	2.3	-16.9	-8.6
	19%	8.4	-3.4	***1.7***
	21%	6.4	-3.9	0.5
	23%	7.3	-5.1	0.2
L2	15%	1.8	-18.3	-9.7
	19%	9.3	-4.2	***1.6***
	21%	6.1	-3.5	0.6
	23%	7.9	-6.2	-0.1
L3	15%	3.0	-16.4	-8.1
	19%	8.0	-4.0	***1.2***
	21%	5.2	-2.6	0.8
	23%	5.4	-3.9	0.1

Table 4.3. Percent Travel Time Savings for 100% Demand
(Calibration of target occupancy for ALINEA)

Detector Location	***Scenario***	***Mainline***	***Ramps***	***Total***
L1	15%	6.1	-10.3	-3.4
	19%	11.8	0.1	***5.0***
	21%	12.4	-0.5	4.9
	23%	8.1	-6.1	-0.1
L2	15%	1.2	-16.3	-8.9
	19%	11.0	-2.4	***3.2***
	21%	6.1	-11.5	-4.1
	23%	5.2	-11.3	-4.4
L3	15%	1.1	-18.2	-10.1
	19%	10.3	-3.7	***2.2***
	21%	8.1	-3.8	1.2
	23%	6.2	-7.9	-2.0

Furthermore, the trend in the results for 90% and 100% demand clearly demonstrates the superiority of 19% occupancy. It was believed that the same trend would continue for higher demand levels. Therefore, calibration of occupancy was not carried out for 110% and 120% demand. During the calibration of target occupancy, the downstream condition was bottleneck-free. This was done in order to represent an ideal condition for ALINEA that assumes no downstream bottleneck.

4.1.1.2 Mainline detector location

As described earlier, three mainline detector locations were tested for Ramp LL. Since there was no improvement caused by metering for 80% demand case, it was decided not to use this demand level for this part of the study. 19% target occupancy was used for all experiments. The implementation of ALINEA assumes no downstream bottleneck. However, the situation in the real world is frequently different. Therefore, based on our discussions in Chapter 3, we identify the "best" mainline detector location for two downstream conditions - "Condition 1" and "Condition 2" .

Table 4.4. Percent Travel Time Savings for 90% Demand (19% Target Occupancy)
(Calibration of mainline detector location for ALINEA)

Detector Location	***D/S Condition***	***Mainline***	***Ramps***	***Total***
L1	Condition 1	7.7	-2.4	2.0
L2	Condition 1	8.4	-1.5	***2.8***
L3	Condition 1	4.6	-4.5	-0.6
L1	Condition 2	8.4	-3.4	***1.7***
L2	Condition 2	9.3	-4.2	1.6
L3	Condition 2	8.0	-4.0	1.2

The results for 90% and 100% OD demand are shown in Tables 4.4 and 4.5 respectively. It can be seen from the tables that in the absence of downstream bottleneck, it was better to maintain target occupancy at L1 for both 90% and 100% demand. Due to the improved downstream condition, the congestion was primarily due to the merging traffic from Ramp LL (as contrast to the other case where the congestion was possibly due to the downstream bottleneck) and therefore, it made sense to maintain target occupancy at the merge. However, when there was a downstream bottleneck, the results suggest that target occupancy should be maintained at L2 for both demand levels. The location L3 produced the worst result for both the downstream conditions. This was perhaps because of unstable traffic conditions at L3. Due to rapid queue formations and dissipations at L3, (as L3 was located very close to the downstream bottleneck) the measurement at this location was not reliable. For the comparison study in the second stage, we decided to use L1 when there is no downstream bottleneck and L2 when there is a downstream bottleneck. For the reasons described during calibration of target occupancy, we decided not to simulate higher demand levels for calibration of detector location.

Table 4.5. Percent Travel Time Savings for 100% Demand (19% Target Occupancy)
(Calibration of mainline detector location for ALINEA)

Detector Location	***D/S Condition***	***Mainline***	***Ramps***	***Total***
L1	Condition 1	6.9	-3.8	0.7
L2	Condition 1	8.8	-1.9	***2.6***
L3	Condition 1	0.7	-13.8	-7.7
L1	Condition 2	11.8	0.1	***5.0***
L2	Condition 2	11.0	-2.4	3.2
L3	Condition 2	10.3	-3.7	2.2

4.1.2 Calibration Results for FLOW

Two influence zones (Figure. 3.7) were used for calibrating FLOW. We obtained conclusive results regarding the calibration of input parameters for ALINEA with 90% and 100% demand. But, that was not the case for calibrating the influence zone for FLOW. Therefore, three levels of OD demand - 90%, 100% and 110%, and two downstream conditions - bottleneck and no bottleneck, were simulated. 80% demand level was not used for this case for reasons described earlier. Tables 4.6 through 4.8 present the result of the calibration study.

For all demand levels, it can be seen that influence zone 1 outperformed influence zone 2 when there was a downstream bottleneck. This was because the location of the downstream bottleneck was within the influence zone 1 but outside the area of influence zone 2. As a result, the bottleneck was identified and taken into account in metering rate calculation more efficiently by influence zone 1 than influence zone 2. It should be mentioned here that we decided to use the same influence zone for a particular downstream condition for all the demand levels. We see a reverse trend in the results when there was no downstream bottleneck (Condition 2). Although, influence zone 1 resulted in marginal improvement compared to influence zone 2 at 110% demand, influence zone 2 considerably outperformed influence zone 1 at 90% and 100% demand level. Furthermore, even though travel time increased for all cases when metering was used compared to the no control case, the travel time increase was significantly smaller for influence zone 2. In case of no downstream bottleneck, the critical disturbance was created in the merging area of Ramp LL which was incorporated in the metering rate calculation more efficiently by the influence zone 2. This led us to select influence zone 2 for further use, when there was no downstream bottleneck.

Table 4.6. Percent Travel Time Savings for 90% Demand
(Calibration of influence zone for FLOW)

Downstream Condition	***Influence Zone***	***Mainline***	***Ramps***	***Total***
Condition 2	Influence Zone 1	3.3	-14.2	-6.6
Condition 2	Influence Zone 2	4.2	-13.4	***-5.8***
Condition 1	Influence Zone 1	3.6	-7.3	***-2.6***
Condition 1	Influence Zone 2	3.4	-8.4	-3.3

Table 4.7. Percent Travel Time Savings for 100% Demand
(Calibration of influence zone for FLOW)

Downstream Condition	***Influence Zone***	***Mainline***	***Ramps***	***Total***
Condition 2	Influence Zone 1	-2.1	-24.5	-15.1
Condition 2	Influence Zone 2	5.9	-11.0	***-3.9***
Condition 1	Influence Zone 1	8.1	-0.7	***3.0***
Condition 1	Influence Zone 2	3.1	-8.6	-3.7

Table 4.8. Percent Travel Time Savings for 110% Demand
(Calibration of influence zone for FLOW)

Downstream Condition	***Influence Zone***	***Mainline***	***Ramps***	***Total***
Condition 2	Influence Zone 1	18.8	15.6	16.7
Condition 2	Influence Zone 2	16.3	12.2	15.6
Condition 1	Influence Zone 1	7.4	5.6	***6.2***
Condition 1	Influence Zone 2	9.3	1.4	4.2

Based on the above findings, it was decided to use influence zone 1 in presence of downstream bottleneck and influence zone 2 when there was no bottleneck downstream, for the second stage (comparison of the algorithms using fractional experimental design) of our evaluation study.

The "best" values of the parameters obtained form the calibration results which are used for the comparative study in the next section are presented in Table 4.9.

Table 4.9. Summary of Calibration Results

Algorithm	***Downstream Condition***	
	Condition 1	***Condition 2***
ALINEA	L2, 19%	L1, 19%
FLOW	Influence Zone 1	Influence Zone 2

4.2 Results of the Comparison Study

The comparison of the two algorithms was done with respect to three experimental factors: traffic demands, downstream conditions, and queue override policies. The experimental factors and their levels were discussed in Chapter 3. In this section, the results from the comparative study of the algorithms are presented in the form of percentage travel time savings in Tables 10 through 17. As mentioned in Section 4.1, a positive or a negative sign associated with percent travel time savings indicates travel time reduction and increase respectively. The results are organized in three parts. The first part describes the effect of the downstream bottleneck whereas the second and third parts describe the effects of demand and queue override strategy respectively.

4.2.1 Effect of Downstream Bottleneck

First we compare the performance of ALINEA and FLOW in the presence and absence of downstream bottleneck when no queue override was in place (Tables 4.10 and 4.11). ALINEA performed better than FLOW when Ramp C was metered and there was no queue override (Table 4.10). This is because ALINEA is a local control algorithm and this situation was ideal for its implementation. However, FLOW performed better than ALINEA (Table 4.11) when Ramp C was not metered (except for 80% demand). Considering that ALINEA does not account for the downstream bottleneck, this result is self-explanatory. Also, FLOW has an additional queue override condition. As a result, the delay for Ramp LL traffic was much larger for ALINEA than that for FLOW.

Tables 4.12 and 4.13 represent the performance of the algorithms for both downstream conditions in case of 100% queue override policy. With this policy in use and in presence of the downstream bottleneck (Table 4.12), ALINEA was better at low demand (90%), whereas FLOW showed more improvements at high demand (110%). At low demand, the effect of the downstream bottleneck was not pronounced and therefore local control strategy of ALINEA was able to maintain the desired level of occupancy on the mainline, without severely penalizing Ramp LL traffic. But, similar to our findings from Table 4.10, ALINEA performed better than FLOW (Table 4.13) in the absence of any downstream bottleneck for 100% queue override strategy.

ALINEA was better (downstream bottleneck and 75% queue override strategy) at low demand (90%), whereas FLOW showed more improvement for high demand (110%) (Table 4.14). This was due to the same reason that we explained for the 100% queue override strategy case. Tables 4.15 through 4.17 further substantiate the previous finding that ALINEA was more effective at moderate/high demand with no bottleneck, whereas, FLOW performed better at high demand levels with bottleneck, disregarding the queue override strategies. The only exception was for 110% demand (no D/S bottleneck and 62.5% queue override), where the performance of ALINEA and FLOW was comparable.

Table 4.10. Percent Travel Time Savings (No D/S Bottleneck, No Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
90%	10.9	9.7	-38.3	-7.6	-3.7
110%	53.8	69.9	-76.4	-170.7	-6.7
FLOW					
90%	14.5	7.4	-34.3	-46.4	-8.3
110%	55.8	63.3	-7.4	-370.2	-16.9

Table 4.11. Percent Travel Time Savings (D/S Bottleneck, No Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
80%	0.1	-1.5	-4.1	-1.0	-1.4
100%	23.6	25.4	-133.4	6.6	-18.5
120%	45.7	35.5	-170.5	5.3	-20.9
FLOW					
80%	0.5	-5.1	-18.8	-0.1	-5.0
100%	18.3	1.2	-93.8	3.0	-15.5
120%	43.8	16.2	-77.0	11.6	-0.6

Table 4.12. Percent Travel Time Savings (D/S Bottleneck, 100% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
90%	8.4	8.0	-12.4	3.8	2.8
110%	8.3	13.5	-10.4	4.9	4.3
FLOW					
90%	3.6	1.0	-20.5	2.0	-2.6
110%	7.4	15.6	-5.7	8.9	6.2

Table 4.13. Percent Travel Time Savings (No D/S Bottleneck, 100% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
80%	0.2	0.0	-0.8	0.3	0.0
100%	11.8	14.6	-2.8	-11.4	5.0
120%	14.5	19.8	5.9	-5.5	10.5
FLOW					
80%	0.8	-1.1	-22.0	-20.4	-8.5
100%	5.9	4.4	-18.2	-16.5	-3.9
120%	10.9	17.0	1.4	-11.1	6.5

Table 4.14. Percent Travel Time Savings (D/S Bottleneck, 75% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
90%	6.0	5.1	-8.5	1.8	-1.8
110%	13.5	23.3	4.7	12.4	13.5
FLOW					
90%	3.4	-0.2	-13.2	1.1	-1.4
110%	14.4	26.6	7.1	17.4	16.0

Table 4.15. Percent Travel Time Savings (No D/S Bottleneck, 75% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
80%	-0.2	-0.1	-5.7	-1.2	-1.6
100%	9.0	11.2	-2.8	-7.9	3.8
120%	12.0	18.3	5.9	6.7	11.2
FLOW					
80%	-0.1	-2.2	-16.1	-15.2	-6.8
100%	3.8	4.2	-10.8	-11.1	-2.1
120%	17.3	18.2	5.1	-1.2	11.4

Table 4.16. Percent Travel Time Savings (D/S Bottleneck, 62.5% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
80%	-0.7	-1.5	-3.3	-0.9	-1.5
100%	5.1	5.8	-5.3	0.9	1.9
120%	6.1	9.8	0.7	6.7	5.7
FLOW					
80%	-0.4	-2.2	-12.0	-0.7	-3.4
100%	-2.6	-9.7	-15.2	-7.0	-7.7
120%	8.5	8.5	2.5	8.4	6.9

Table 4.17. Percent Travel Time Savings (No D/S Bottleneck, 62.5% Queue Override)

Demand	Mainline	Ramp II	Ramp LL	Ramp C	Total
ALINEA					
90%	5.8	4.8	-4.5	-4.9	1.5
110%	12.0	21.4	7.6	-5.6	10.8
FLOW					
90%	0.2	-2.5	-11.6	-14.9	-5.5
110%	10.6	18.7	7.3	-3.8	9.8

4.2.2 Effect of Demand

It was observed (Tables 4.11, 4.13, 4.15, and 4.16) that at 80% OD demand, ramp metering did not produce any improvement for any of the experimental scenarios tested in this study. On the contrary, traffic condition deteriorated in all these scenarios as a consequence of metering. At this level, the demand was too low to warrant any metering. As a result, vehicles were unnecessarily held back on the ramps due to metering. This additional penalty to the ramp vehicles caused deterioration in system performance.

For both downstream conditions, when the queue override strategy was not in place, it can be noted (Tables 4.10 and 4.11) that for all levels of demand, metering caused significant deterioration in system travel time for both the algorithms. This deterioration increased with increasing level of demand. It can be concluded that the overall system performance at higher demands is more severely affected by the absence of queue override strategy than at lower demands.

Except for the hypothetical scenario of "no queue override", both algorithms produced higher travel time savings for higher demand levels. This may suggest testing the algorithms for demand levels higher than 120%. However, it should be noted that at 120% demand, the delay in the entire network is unrealistically large. Therefore, it was not practical to test demands over 120%. In case of ALINEA, there was always an improvement (increasing with higher level of demand) due to ramp metering for all demand levels except 80%. It suggests that ALINEA is an efficient ramp control strategy for moderately high demand and above. On the other hand, FLOW did not show (Tables 4.12-4.17) any system wide improvement for 90% and 100%. However, there was a significant improvement in network performance for higher levels (110% and 120%) of demand. FLOW is an area wide metering algorithm. It takes the system wide bottleneck effects into consideration. At 110% and 120% demand levels, the entire system was very congested and as a result, bottleneck could have formed at other locations. It seems that FLOW, being a coordinated algorithm, could account for these bottlenecks at unexpected locations.

4.2.3 Effect of Queue Override Strategy

For both algorithms, when the queue override strategy was not employed, the system was adversely affected by ramp metering (Tables 4.10 and 4.11). In no queue override scenario, ramp vehicles were highly penalized by metering. This caused significant improvement on the mainline. However, it was found that the deterioration in the ramp traffic conditions, by far, outweighed the improvement on the mainline, causing an increase in total travel time. Also, it may not be feasible, both from an operational as well as equity standpoint, to adopt this strategy. Thus, it is concluded that the queue override strategy should always be implemented. It should be mentioned that the no queue override strategy caused significant deterioration in the performance of the metered ramps because of very high ramp demands for the CA/T network. It may not show similar effects for other networks where on-ramp demands are relatively low.

The other three queue override strategies for ALINEA caused overall improvement in the system for traffic demand of 90% or higher (Tables 4.12-4.17). It is interesting to note that for very high traffic demand (110% and 120%), the 75% queue override strategy performed better than the 100% strategy for both algorithms. Although such impacts of queue override strategy are not clear and further investigations are strongly recommended, we propose the following conjecture to explain the phenomenon. At very high demand levels, mainline was congested due to its own demand and therefore, any attempt to maintain an optimal occupancy would not be successful. Furthermore, in the process of a futile attempt to maintain an optimal occupancy, ramp meters might have caused more delay to the ramp traffic than the savings to the mainline traffic. When 100% strategy was used, ramp meters were allowed to operate for a larger duration than the 75% strategy. Given that ramp meters were not able to achieve desired flow, a strategy with shorter duration of operation, i.e. 75%, resulted in a better performance.

Results for 62.5% strategy were similar to the 100% case. It performed better than no control and no queue override but worse than 75%. It seems that the use of 62.5% of the physical ramp length for queue override might have caused more frequent suspension of metering operations than necessary. Therefore, based on our results, the 75% queue override strategy appeared to be a good compromise.

4.3 Regression Results

While the tabular analysis of the previous sections implicitly demonstrated the effect of experimental factors on the performance of the algorithms, a regression analysis of the results explicitly quantifies the impact of different variables. Also, it is possible to get the interaction effect of the experimental variables using regression. Next we present and analyze results from a linear regression analysis performed on data presented in the last section.

Percent travel time savings were used as the dependent variable. Dummy variables were used to represent different levels of different experimental factors. We included an intercept term in the regression equation to represent the base case. In all the regressions, the base case was selected as 100% demand, no downstream bottleneck and no queue override.

4.3.1 Regression Analysis of ALINEA

We first ran a regression to check only the main effects of the experimental variables. There were eight dummy variables (four for traffic demand, one for downstream condition, and three for queue override strategy) and an intercept. The regression equation is –

$$y = \beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_5X_5+\beta_6X_6+\beta_7X_7+\beta_8X_8+\varepsilon \quad \text{where,}$$

$x1= 1$ if 80% Demand
$x1= 0$ if otherwise
$x2= 1$ if 90% Demand
$x2= 0$ if otherwise
$x3= 1$ if 110% Demand
$x3= 0$ if otherwise
$x4= 1$ if 120% Demand
$x4= 0$ if otherwise

$x5= 1$ if D/S Bottleneck
$x5= 0$ if otherwise

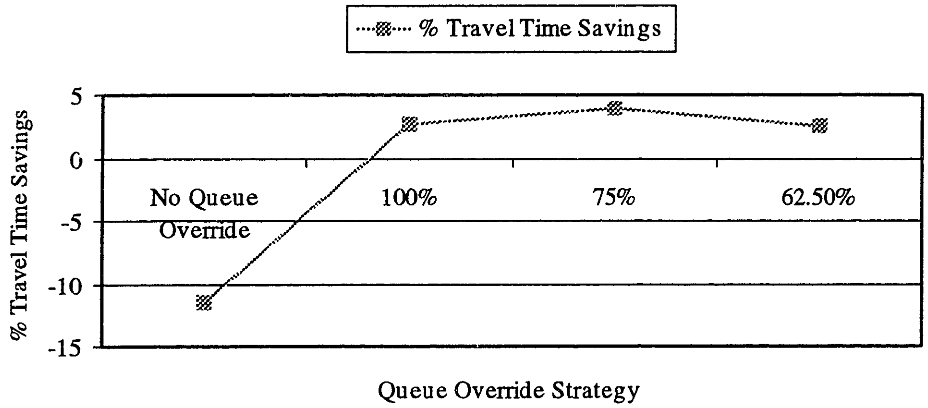
$x6= 1$ if 62.5% Queue Override
$x6= 0$ if otherwise
$x7= 1$ if 75% Queue Override
$x7= 0$ if otherwise
$x8= 1$ if 100% Queue Override
$x8= 0$ if otherwise

	Coefficients	***Standard Errors***	***t Statistics***
β_0	-11.468	4.453	-2.575
β_1	0.830	4.569	0.181
β_2	1.529	4.569	0.335
β_3	7.443	4.569	1.629
β_4	3.570	4.569	0.781
β_5	-2.729	2.949	-0.925
β_6	13.931	4.086	3.408
β_7	15.434	4.129	3.737
β_8	14.198	4.129	3.438
Adjusted R Square = 0.461			

Table 4.18. Main Effects for ALINEA

The regression results are presented in Table 4.18. The intercept term (β_0) is statistically significant as evident from its very high t statistics. Its value is also very high which indicates that there is almost 11.5% total travel time increase for the combination of 100% demand, no downstream bottleneck and no queue override. The coefficients (β_1, β_2) corresponding to the demand levels 80% and 90% are statistically not significant at any reasonable level and their magnitudes are also low. This indicates that the performance of ALINEA is not very sensitive to low demands (80% and 90%). However, if we look at the magnitude of the coefficient (β_3), it seems that there is a significant improvement in percent travel time savings for 110% demand compared to the 100% case and its t statistics is also significant. The coefficient (β_4) corresponding to 120% demand is not statistically significant but its magnitude indicates considerable travel time savings. Perhaps, this high demand level is causing other effects in the network, e.g. formation of downstream bottleneck, that could be better explained with the help of interaction variables. The downstream bottleneck coefficient (β_5) is statistically not significant, but has intuitive sign. As ALINEA assumes a bottleneck-free downstream, the presence of a downstream bottleneck should adversely affect its performance. All the queue override coefficients (β_6, β_7, β_8) are statistically significant and their magnitudes are also large, indicating significant travel time savings compared to the base case. It can be seen (from Table 4.18 and Figure 4.1) that the travel time savings are highest for 75% queue override strategy followed by 100% and then 62.5%. This result is consistent with our earlier findings in the previous section where a possible explanation for this observation was also provided. From Table 4.18, it can be

Fig. 4.1. Effect of Queue Override Strategy for ALINEA



noticed that the values of standard errors for all/some coefficients of different experimental factors are equal. This is due to the orthogonal fractional design that was used to capture the relevant effects of the variables with no correlation.

For our next regression model formulation, we retained all the main effect variables and tried some interaction variables in our model. The interaction variables were constructed based on our judgement and understanding of their impacts. We tried interactions with the 120% demand variable to examine the effect of very high demand in combination with a downstream bottleneck and with no queue override. The 120% demand and downstream bottleneck interaction is expected to have detrimental effect on ALINEA. Since, ALINEA can not incorporate the presence of downstream bottleneck, a combination of higher demand and downstream bottleneck is expected to magnify the detrimental effect. The interaction of 120% demand and no queue override is expected to cause severe deterioration in the system performance. From our first regression model and from our analysis in the previous section, it was observed that no queue override had significant detrimental effect on the system. So, its combination with very high level of demand should further worsen the situation. The other interaction variable tried was 80% demand and downstream bottleneck. In case of 80% demand alone, the demand was too low to warrant any metering. However, a downstream bottleneck may cause propagation of congestion from downstream which may give rise to a situation when an improvement in system performance could be obtained by the metering. But it was found that the coefficient corresponding to this interaction was statistically not significant and its value was also found to be low. Therefore, even in the presence of downstream bottleneck, ramp metering with ALINEA does not have any significant impact on the system performance in case of low demand. This further confirmed our earlier finding about the insensitivity of ALINEA to low demand levels.

The final regression equation is given by

$$y = \beta'_0+\beta'_1X_1+\beta'_2X_2+\beta'_3X_3+\beta'_4X_4+\beta'_5X_5+\beta'_6X_6+\beta'_7X_7+\beta'_8X_8$$
$$+\beta'_9(X_4X_5)+\beta'_{10}(X_4(1-X_6-X_7-X_8))+\varepsilon$$

where the variables are defined as before. The regression results are presented in Table 4.19.

	Coefficients	***Standard Errors***	***t Statistics***
β'_0	-9.881	3.846	-2.569
β'_1	0.830	3.846	0.216
β'_2	1.530	3.846	0.398
β'_3	7.443	3.846	1.935
β'_4	9.453	5.088	1.858
β'_5	-0.769	2.719	-0.283
β'_6	10.757	3.846	2.797
β'_7	11.886	3.748	3.171
β'_8	10.651	3.748	2.841
β'_9	-3.830	7.928	-0.483
β'_{10}	-15.873	8.600	-1.846
Adjusted R Square = 0.62			

Table 4.19. Main and Interaction
Effects for ALINEA

The effects of variables X_1, X_2, X_3, X_5, X_6, X_7, X_8 on the performance of ALINEA show the same trend as before as indicated by the sign and magnitude of their coefficients. It is interesting to note that, in this model, the inclusion of interaction variables significantly increased the magnitude and the significance of the coefficient (β'_4) of 120% demand. So, it confirmed our a priori belief that at this high demand level, interactions among demand and other variables (such as bottleneck) may have significant impact on system performance. The signs and the magnitudes of the coefficients (β'_9 *and* β'_{10}) for the interaction variables also conform to our a priori expectations. The results indicate that the combination of 120% demand and downstream bottleneck considerably worsened the system performance. The variable 120% demand and no queue override caused severe system deterioration as expected. It should be noted that the increase in travel time due to this interaction is significantly higher than that caused by no queue override in the base case. These results are interesting in the sense that 120% demand alone did not have these significant effects on the performance of ALINEA, but in combination with other variables it was found to affect the performance of ALINEA considerably. Also, the adjusted R^2 value for this regression model indicates that this model had a better fit than the previous model.

4.3.2 Regression Analysis of FLOW

We also performed similar regression analysis on the results obtained for FLOW. For the first regression model, we used the same main effect variables and intercept, as in ALINEA. The base case is also the same. The regression results for this model are presented in Table 4.20.

	Coefficients	*Standard Errors*	*t Statistics*
β_0	-16.805	3.934	-4.271
β_1	1.353	4.036	0.335
β_2	1.846	4.036	0.457
β_3	11.078	4.036	2.745
β_4	13.342	4.036	3.306
β_5	3.062	2.605	1.175
β_6	9.253	3.610	2.563
β_7	13.269	3.648	3.638
β_8	9.400	3.648	2.577
Adjusted R Square: 0.566			

Table 4.20. Main Effects for FLOW.

The intercept term (β_0) is very significant and its sign and magnitude indicate that the combination of 100% demand, no downstream bottleneck and no queue override causes significant deterioration of the performance of the algorithm. The coefficients (β_1 and β_2) for 80% and 90% demand are statistically not significant and their magnitudes are also low. It suggests that, everything else being same, performance of FLOW is not affected at low demand (less than 100%). However, the effect of higher demand levels (110% and 120%) on the performance of FLOW is very significant with more system-wide improvement at higher demand, as evident by the coefficients' (β_3 and β_4) magnitudes and their statistical significance. At these demand levels, congestion is likely to be created at many locations. FLOW, being a coordinated algorithm, seems to react to them effectively. This confirms our observation from the tabular analysis in the previous section. The magnitude and the statistical significance of downstream bottleneck coefficient (β_5) are not very high. This is understandable, because the presence/absence of a downstream bottleneck should not affect the performance of FLOW (An ideal coordinated algorithm is supposed to be equally effective for all bottleneck locations within the influence zone). The sign of β_5 is also intuitive. It indicates that, unlike ALINEA, there is an improvement in system performance in the presence of downstream bottleneck because of the coordinated nature of FLOW. The statistical significance and the magnitude of all the queue override coefficients (β_6, β_7, β_8) are very high, indicating that FLOW is also very sensitive to queue override policy. Also, its performance is best for 75% queue override similar to ALINEA. This result is again consistent with our prior findings in Section 4.2.3.

For the next regression models, we kept all the main effect variables and also tried the same interaction variables for FLOW, as were used for ALINEA. It is interesting to note that one of the interaction variables that was found to be very significant in case of ALINEA was statistically insignificant in this case and its coefficients was also small in magnitude. The variable was 120% demand and downstream bottleneck. At a demand level of 120%, the network is very congested and the interaction with bottleneck may further deteriorate the system. However, most of this effect of high congestion is explained by the demand variable alone in case of FLOW. Besides, FLOW, being a coordinated algorithm, takes into account the presence of downstream bottleneck during its metering rate calculation. As a result, this interaction term is not significant. The results for the 80% demand and downstream bottleneck interaction variable were similar to ALINEA, indicating the insensitivity of FLOW to low demands. Although, its coefficient was not statistically significant, the interaction term that considerably affected the performance of FLOW in terms of coefficient value, was 120% demand and no queue override. Therefore, it was decided to keep this interaction term in our final regression model.

So, the new regression equation is –

$$y = \beta''_0+\beta''_1X_1+\beta''_2X_2+\beta''_3X_3+\beta''_4X_4+\beta''_5X_5+\beta''_6X_6+\beta''_7X_7+\beta''_8X_8$$
$$+\beta''_9(X_4(1-X_6-X_7-X_8))+\varepsilon$$

The regression results are presented in Table 4.21.

	Coefficients	***Standard Errors***	***t Statistics***
β''_0	-16.769	4.202	-3.991
β''_1	1.353	4.233	0.320
β''_2	1.846	4.233	0.436
β''_3	11.078	4.233	2.617
β''_4	13.432	4.677	2.872
β''_5	3.092	2.812	1.100
β''_6	9.181	4.107	2.236
β''_7	13.203	4.094	3.225
β''_8	9.334	4.094	2.280
β''_9	-4.360	7.952	-0.548
Adjusted R Square = 0.638			

Table 4.21. Main and Interaction
Effects for FLOW.

The intercept term and all the main effect variables show the same trend in results as before (Table 4.20). The sign and magnitude of the coefficient β''_9 indicate that the combination of 120% demand and no queue override caused considerable system travel time increase. But, it is interesting to note that this deterioration in system performance due to the combined effect is significantly milder compared to that of ALINEA which is evident from its coefficient magnitude for this interaction variable (Table 4.19). This is because of our earlier observation that FLOW performs better than ALINEA in a very congested situation and the ramps are severely congested due to the combination of 120% demand and no queue override policy. The second model in this case also had a better fit than the first one.

In this chapter, results from the evaluation study were presented in the following order. First, the results of the calibration study of the input parameters were illustrated. Then, the tabular and the regression analysis of the results of the fractional experiments were presented. In the next chapter, we will summarize the research, list the findings and provide scopes for future work.

Chapter 5

Summary, Findings and Future Research

5.1 Summary

Ramp metering has emerged as an effective freeway control measure to ensure efficient freeway operations. A number of algorithms have been developed in recent years to ensure an effective use of ramp metering for better traffic management. As the performance of ramp metering depends on various factors (e.g. traffic volume, downstream traffic conditions, queue override policy etc), these algorithms should be evaluated over a wide range of traffic conditions to check their applicability and performance. In view of the expense of and confounding effects in field testing, simulation plays an important role in the evaluation of such algorithms.

This research presented the two stage evaluation of two ramp metering algorithms: a local control algorithm (ALINEA) and a coordinated algorithm (FLOW) using MITSIM laboratory with respect to a wide variety of traffic conditions. It demonstrated the usefulness of the proper calibration of the algorithms, the impact of different traffic variables on the performance of these algorithms and their complex interactions with ramp metering and the use of a systematic experimental design and microscopic simulation for ramp metering evaluations. The evaluations were performed for the Central Artery/Tunnel network in Boston. In the first stage, key input parameters for the algorithms (target occupancy and mainline detector location for ALINEA and influence zone for FLOW) were identified and calibrated. The calibrated parameters were then used for the second stage, where the algorithms were compared using an orthogonal fraction of experiments. In the comparative study, the performance of the algorithms with respect to three traffic variables (traffic volume, downstream traffic conditions, queue override policy) were evaluated to study their impacts on ramp metering and to derive insights.

5.2 Findings

A number of conclusions can be drawn based upon this research. This research was a successful demonstration of the evaluation of ramp metering algorithms with a microscopic simulation laboratory. To the best of our knowledge, this is the first study to use microscopic simulator to evaluate ramp control algorithms for such a large number of variables. Findings from this study can be summarized as follows:

1) Ramp metering significantly increased the system travel time for a large number of scenarios, particularly at low demand levels. For ALINEA, the deterioration in system performance was observed at 80% demand, whereas, for FLOW it was observed at demand levels lower than 110% indicating the usefulness of FLOW only at very high demands.
2) In almost all the scenarios (except 80% demand) ramp metering understandably improved mainline traffic conditions for both algorithms. In addition to these improvements, the algorithms with properly calibrated input parameters caused no penalties to the ramp traffic or even decreased the total travel time of ramp traffic for high demands when a queue override strategy was implemented.
3) When ramp queue was allowed to build up infinitely, substantial increase in ramp travel time was observed for both the algorithms. This deterioration increased with increasing level of demand. This observation suggests that queue override should always be used.
4) When there was no bottleneck downstream of the metered ramps, the performance of ALINEA, as expected, was satisfactory. However, under a downstream bottleneck scenario, it was found that FLOW outperformed ALINEA because of the coordinated nature of FLOW.
5) At very high demand levels (110% and 120%), the travel time improvements in FLOW were higher than those in ALINEA. At those demand levels, congestion could have occurred at unexpected locations. FLOW, being a coordinated algorithm, could account for unspecified congestion spots.
6) It was found that when ramp queues were allowed to build up to 75% of the physical length of the on-ramp (before metering was suspended), the algorithms' performance was better than that in the scenario in which queue was allowed on the entire length of the on-ramp.

Although, we do not clearly understand the reasons behind this phenomenon, we believe that it is happening due to a possible overuse of ramp metering when the mainline is congested due to a high demand on the mainline itself.

7) Regression was used to analyze the evaluation results. It helped identify the previously unexplored impacts of some of the interactions among the experimental factors on the performance of the algorithms, which was not otherwise possible with a tabular analysis.

5.3 Future Research

Although this research presented a detailed evaluation of ramp control algorithms, further efforts are needed to understand the impacts of and interactions between different variables that affect the ramp metering performance. The scopes for future research include:

- It was found that at lower demand levels, ramp metering significantly deteriorated overall system performance. This suggests the need for future research to develop a real-time procedure to suspend metering operations when they are not warranted.
- One of the significant findings of this research was the improved performance produced by the scenarios at which 75% of the physical ramp length was used for queue storage compared to the total length. A conjecture was provided to explain this phenomenon. Further studies are strongly recommended to understand and analyze this impact in order to substantiate this finding.
- The following findings of this research – improvements in ramp traffic conditions by metering and the effect of ramp queue storage length may depend on the very high ramp demands for this test network. Jha and Bierlaire (1998) has expressed the downstream (of an on-ramp) mainline throughput as a function of mainline and ramp demand. They have shown that for a given mainline demand, if the ramp demand is kept increasing, a point will be reached for which the mainline throughput will be maximum. Increasing the ramp demand above this point will cause traffic to break down due to the disturbance created by the friction between two (mainline and ramp) traffic streams and mainline throughput will eventually decrease to a constant value when the network will be saturated. This suggests

that the performance of ramp metering may significantly depend on the ramp demands. But, the impacts of traffic demand were evaluated in this study by varying the mainline and the ramp demands simultaneously. Therefore, future studies should check the effects of different combinations of mainline and ramp demands on ramp metering.

- The urban road network was not simulated in this study. As a result, drivers' diversion behavior at the on-ramps was not modeled. For future studies, the diversion strategy should be modeled to study the impact of route diversion on the performance of ramp metering.
- In case of traffic signals upstream of an on-ramp, the arrival pattern of the vehicles may depend on the phasing and timing of the signals. The arrival pattern of vehicles at on-ramps may have significant impact (Cuneo, 1998) in merging operations. Thus, evaluation of ramp metering should account for the impact of upstream traffic signals.
- A field study is desirable to validate the findings of this evaluation study.

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