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16. Abstract (Limit: 200 words)  
This project involved a detailed review of coordinated metering algorithms currently operating in the United States and a simulation analysis to examine the performance of three algorithms that represent each coordination approach; the Denver incremental coordination, the Seattle Fuzzy metering and the Minnesota explicit section-wide coordination approaches.

Researchers used a macroscopic simulation model with the same geometry and traffic demand conditions. Based on the analysis results, they developed alternative metering approaches by combining conventional zone-wide control with fuzzy coordination. They also developed two new alternative procedures to estimate bottleneck capacities in real time; an adaptive estimation method using Kaman Filter and a neural-network based approach that predicts traffic volume for a given mainline location using traffic data collected from upstream and downstream detectors. Both approaches were tested with the real data collected from the sample freeway sites. The preliminary test for alternative strategies using simulation with an example freeway in Minnesota showed promising results in terms of reducing congestion and increasing throughput on the mainline. Further testing and research is recommended.

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CAPACITY ANALYSIS FOR DYNAMIC BOTTLENECKS AND ALTERNATIVE CONCEPTS FOR COORDINATED RAMP METERING OPERATIONS

Final Report

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EXECUTIVE SUMMARY

Ramp metering has long been recognized as one of the most effective tools that can optimize the operations of a freeway system with given management objectives. While various optimal metering strategies have been proposed by different groups of researchers, most methods found in the literature adopt model-based, multi-layer hierarchical control structures. These methods decompose the overall freeway control into several components, such as on-line origin/demand prediction, determination of ‘optimal traffic state’ from corridor-wide optimization and the adjustment of real traffic conditions to the nominal state through a direct control layer. While this concept is promising, the difficulties in predicting origin/destination demand in real time, inherent limitations in modeling the behavior of complex traffic flows and the lack of reliable sensors that can directly measure ‘traffic state’ have forced traffic engineers to adopt much simpler heuristic approaches that do not employ on-line prediction or optimization. This research performs a detailed review of the operational metering algorithms that adopt real-time, coordinated control approaches. Further, the simulation analysis was also conduced with the selected algorithms to identify the performance patterns of each metering approach.

The operational metering algorithms for on-line coordinated control can be classified into three categories; 1) the bottleneck-based, section-wide coordination approach being employed by Minnesota, Virginia and California, 2) the incremental group coordination approach being implemented in Denver, Colorado, 3) the fuzzy logic-based implicit coordination method of the Seattle, Washington, system. The bottleneck-based section-wide control methods represent the conventional concept of maximizing flow levels at pre-determined bottlenecks by simultaneously determining the metering rates of all the entrance ramps in a section with given link capacity and expected demand. In the Virginia and California algorithms, the structure of metering sections is fixed, while the Minnesota algorithm combines the volume-based fixed-section and the occupancy-based moving-section approaches. The incremental coordination approach sequentially restricts the metering rates of upstream ramps by one level whenever a ramp operates at the ‘critical mode’, i.e., at its most restrictive rate or in a queue override mode. This upward rate adjustment continues one ramp at a time until the ramp in question becomes not critical. In the Seattle fuzzy metering system, the coordination of multiple ramps is implicitly incorporated into the rate calculation process by sharing common set of data in determining individual metering rates. A set of fuzzy membership functions and rules that relate the traffic
measurements to metering rates need to be determined for each meter, while the weight of each rule can be changed in real time to reflect certain management objectives. Both incremental coordination and fuzzy metering algorithms try to identify bottlenecks in real time and do not explicitly require the estimation of link capacity values or prediction of traffic demand. Further, most operational metering systems adopt some form of ramp-queue management policies, i.e., either fixed-threshold or incremental adjustment strategies, while Minnesota and San Diego are the only systems that do not employ an explicit queue override policy.

The performance analysis using a macroscopic simulation model was conducted for three algorithms representing each coordination approach, i.e., the Denver incremental coordination, the Seattle Fuzzy metering and the Minnesota explicit section-wide coordination approaches, under the same geometry and traffic demand conditions. The simulation results from the incremental and fuzzy metering algorithms indicated potential negative impacts of ramp-queue override policies on the management of mainline congestion. In case of the incremental algorithm, the case without queue control produced better performance than the case with queue control, i.e., more mainline vehicle-miles with less congested vehicle-hours, while the Fuzzy metering without employing queue rules showed compatible vehicle-miles with less congestion than the other cases with queue weights. The performance comparison of the three algorithms indicates that the incremental algorithm with queue-override policy resulted in the most amount of congestion on mainline, while the Minnesota algorithm, which does not employ queue override policies, consistently produced more evenly distributed traffic flows on mainline with lower level of congestion than other algorithms. However, the comparison of the average ramp vehicle-hours indicated that the Minnesota algorithm resulted in more number of ramps with high vehicle-hour values than other algorithms, while the Denver incremental algorithm employing a strong queue-override policy consistently produced the least amount of on-ramp vehicle-hours. It was also noted that the Fuzzy algorithm resulted in more ramp-to-ramp variations in ramp vehicle-hours than other metering methods.

The performance analysis of the three selected algorithms indicates that, with proper calibration of system parameters, there still exists the advantage of explicit section-wide coordination method over the incremental or fuzzy-based, implicit coordination approach in terms of managing mainline congestion by distributing traffic demand over space and time. However, considering the increased frustration level of drivers on ramp waiting time, the balanced management of ramp queue and mainline congestion becomes one of the major issues with the Minnesota algorithm, which has not
adopted explicit ramp-queue management policies. Further, the simplicity of the incremental coordination approach and the flexibility of the fuzzy metering in adjusting system parameters in real time were notable features identified from this analysis.

Based on the above, two new alternative metering approaches were developed and evaluated in this research. The nested-zone method is based on the conventional bottleneck-based zone structure and tries to capture local congestion within a primary zone by introducing sub-nested zones. While in this research only the forward nested-zone concept was implemented, a combined approach with both forward and backward nested zones needs to be tested in the subsequent research. The other method presented in this research employs adaptive metering method with fuzzy-based coordination. It is based on the conventional zone-based control structure, but treats a zone as a control unit and employs a fuzzy logic-based intra-zone coordination scheme. Further newly defined congestion index is used to quantify zone-wide congestion level, which makes the new algorithm less sensitive to the detector malfunction. Unlike existing zone-wide coordination methods, the new metering strategy does not require the estimation of link capacity or demand prediction, which has been major difficulty in real time operations. The preliminary test for both alternative strategies using simulation with an example freeway in Minnesota showed promising results in terms of reducing congestion and increasing throughput on the mainline. Further research needs include the extension of the nested-zone metering approach by combining forward and backward zone concepts, so that both forward and backward shock waves can be detected as early as possible. The adaptive metering approach without using predetermined bottleneck capacities also needs further testing. Finally, comprehensive testing of the on-line capacity estimation procedures developed in this research needs to be conducted.
I. INTRODUCTION

1.1 Background and Research Objectives

Ramp metering has been widely considered as one of the most effective tools in managing freeway congestion. While various traffic-responsive optimal metering control methods have been proposed by different groups of researchers, there still exists a substantial gap between theoretical works and the metering algorithms currently in practice. To be sure, most optimal metering strategies proposed in the literature adopt multi-layer hierarchical control structures (1-3), where overall freeway control is decomposed into several components, such as on-line origin/destination demand prediction, determination of ‘optimal traffic state’ from corridor-wide optimization, and finally, the adjustment of real traffic conditions to the nominal state through a direct control layer. While this concept is promising, the difficulties in predicting origin/destination demand in real time, inherent limitations in modeling complex traffic flows and the lack of reliable sensors that can directly measure ‘traffic state’ have forced traffic engineers to adopt much simpler metering approaches, which directly use measured traffic data to determine metering rates without employing on-line prediction or corridor-wide optimization.

The ultimate goal of this research is to develop realistic and robust on-line metering strategies that can determine coordinated control solutions by reflecting network-wide traffic conditions. The specific objectives of the current phase include:

- Review of detailed procedures for currently operational algorithms for coordinated metering control
- Analysis of the performance patterns using macroscopic simulation for selected coordinated metering algorithms,
- Development and evaluation of prototype alternative metering strategies for coordinated control,
- Development and evaluation of prototype bottleneck capacity estimation procedures,
- A series of group meetings with traffic engineers to discuss detailed metering procedures.
1.2 Report Organization

This report summarizes the final results of the current phase, “Capacity analysis for dynamic bottlenecks and alternative concepts for coordinated ramp metering operations”. Chapter 2 of this report describes the detailed procedures of the coordinated metering algorithms currently being operated in the U.S. The development of the simulation modules for the selected metering algorithms and the results from the comparative analysis using simulation are included in the Chapter 3. Chapter 4 develops alternative strategies for coordinated metering. The evaluation results of those alternative concepts using macroscopic simulation are also included in Chapter 4. Chapter 5 contains the real-time bottleneck estimation procedures developed in this research. The conclusions and further research needs are summarized in Chapter 6. Finally, the materials presented at the series of group discussion meetings with the traffic engineers at the Traffic Management Center, Minnesota Department of Transportation (Mn/DOT), as part of this research are included in the appendix.
II. OPERATIONAL ALGORITHMS FOR COORDINATED METERING

II.1 Introduction

Current operational metering systems can be divided into two classes: local control and section-wide coordinated control. Most local control systems use one to three detector stations usually located adjacent upstream and/or downstream of the ramp, whose locations are pre-determined based on past experience. These systems use volume and occupancy measurements with predefined thresholds and select metering rates from rate tables that can vary from ramp to ramp. The systems adopting local control with multiple detector stations include Chicago (4), and Toronto (5), while one detector station is used for the San Diego system (6,7). The key parameters for local responsive metering, i.e., thresholds and rate tables, are in general determined through off-line analysis to optimize the flows at predefined bottlenecks using historical data. In coordinated metering, the metering rates of multiple ramps are either simultaneously or sequentially determined to ensure the flow levels of the bottlenecks, either predefined or identified in real time, can be kept under their capacity values.

The existing coordinated metering approaches can be further classified into three categories, i.e., the incremental group coordination approach being implemented in Denver, Colorado (8-10), the fuzzy logic-based, implicit coordination method in Seattle, Washington (11-13), and the bottleneck-based section-wide coordination strategy being operated by Virginia (14) and Minnesota (15). The new algorithm currently being installed in the Los Angeles area in California also employs a coordinated metering approach with on-line prediction of bottleneck density values (16-18). The rest of this section briefly reviews the major features of those coordinated metering algorithms.

II.2 Denver Metering System

II.2.1 System overview

Denver system currently has 30 ramp meters whose rates are determined every 20 seconds by the combined strategy of Local control, Group coordination, and Queue override (5). The detection system, consisting of double loops located near each entrance ramp, collects volume, occupancy and speed data for each lane every 20 seconds, however, no detectors were installed between two ramps. The metering algorithm uses ‘smoothed 1-minute data’
(smoothing factor: mainline up to 5, ramp 3). Figure 2.1 shows the system map where the congestion level on the mainline is updated every 1 minute with different colors. The typical layout of the detectors at an entrance ramp and nearby mainline is also shown in Figure 2.2. The general features of the Denver system are as follows:

- Each meter has predetermined 6 rates (cycles)
  Originally CDOT used the SafeTran metering controller that has 6 rates and when they installed 170s, they maintained 6-rate scheme for consistency.
- Every 20 seconds, one rate is selected from either local or central controller.
- If communication between local controller and central computer is not working, then all the meters operate in local control mode.
- The local control algorithm is built-in to the local 170 type controller (Firmware by JHK)
- One car per green per lane, but simultaneous release of two vehicles in case of a two-lane ramp
  e.g., if cycle = 2 G + 14 Red = 16 sec. then 2 vehicles are released every 16 sec.
- No separate metering for High Occupancy Vehicles (HOVs).
- Variable Green time: 2.0 to 2.5 sec. (to ensure the passage of slow starting vehicle)
- Green extends until a vehicle passes passage detector
- No yellow signal during regular metering
  (During Start-up phase, Solid Green: 20-25 sec. Y: 5 sec.)
- If no vehicle presents at stop line during metering, Red is extended until a vehicle is detected. Once a vehicle is detected by the presence detector located before the stop line, then one second Red is added before the meter signal turns to Green (2 seconds). After that, normal cycle resumes.
- If a HOV vehicle is detected, then 2–5 Second Red time, depending on the location, is added to current cycle for normal lanes.

**Meter Turn-on and off conditions**

- Each meter has predetermined turn-on/off transition periods and volume/occupancy thresholds
• If local measurements of volume or occupancy from the mainline near a ramp are greater than or equal to predetermined threshold values for “predetermined duration, currently 3 minutes” then metering starts.

• Speed measurements are not currently used for metering control, since they tend to make meters overreact.

• If local measurements of volume or occupancy from the mainline near the ramp are less than or equal to predetermined threshold values for “predetermined duration” then metering stops.

II.2.2 Denver Metering Algorithm

The Denver metering system determines metering rates every 20 seconds by the combined strategy of local control, incremental group coordination and queue override. Currently the system has a total of 30 meters that are divided into four groups. First, each ramp meter collects local volume/occupancy measurements from the mainline detectors located immediately upstream of an entrance ramp. Using a set of predetermined volume/occupancy thresholds, each meter determines a ‘local rate’ by selecting one of 6 metering rates allocated for each ramp. The occupancy measurements from the queue detectors, located near the entrance of each ramp, are used to select the ‘queue rates’ for each ramp with predetermined queue occupancy thresholds. If the queue rate of a meter is less restrictive than its local rate, then the ramp is in ‘queue override’ mode and the local rate is increased by one level until the local rate becomes less than the queue rate.

The group coordination of meters starts when a ramp meter, R_n, becomes ‘critical’, i.e., the ramp is governed by either the most restrictive rate or by queue override. Figure 2.3 illustrates the incremental coordination approach of the Denver algorithm when the meter R_n became ‘critical’ at time k. First, the ramp immediately upstream of a ‘critical’ ramp, R_{n+1}, is assigned one level more restrictive rate than its own local rate at time k + T_{n+1}, where T_{n+1} is the estimated travel time between R_n and R_{n+1} at time k. If R_n is still a critical ramp at the next control time step, then R_{n+2}, i.e., second upstream ramp from the critical ramp is assigned one level more restrictive rate then its own local rate at time k + T_{n+2}, where T_{n+2} is the estimated travel time between R_n and R_{n+2} at k+20 seconds. If any ramp in a ‘group coordination’ mode needs to operate in a queue override mode, then ‘queue override’ overrides ‘group coordination’.
Figure 2.1 Denver system map (screen from WinNT-based RMCS software)
Figure 2.2 Typical layout of detectors at entrance ramp and mainline

* In the above screen, the traffic data, i.e., one minute volume and speed at each detector location, is updated every 1 minute.
Primary group coordination (upstream ramp rate restricted by one level)

Secondary group coordination
(after all the ramps in primary group become critical)

Figure 2.3  Incremental group coordination scheme of Denver metering algorithm
The above procedure is repeated until all the ramps upstream of the critical ramp operate either with the most restrictive rates or in a queue override mode. If a critical ramp still stays as critical after all the upstream ramps in its group operate either with the most restrictive rate or in a queue override mode, then the ‘secondary group coordination’ starts. In this case, the first ramp in the next upstream group is assigned one level more restrictive rate than its own local rate and the same procedure as in the primary group coordination is repeated with all the ramps in the next group. If the critical ramp becomes non-critical, then all the upstream ramps in the ‘group coordination’ mode change to normal local control mode simultaneously (8-10).

As described above, the Denver algorithm tries to determine bottlenecks in real time through on-line identification of ‘critical’ ramps. Further, the incremental coordination approach does not require link capacity values to determine the metering rates for multiple ramps. However, the volume/occupancy thresholds of local control need to reflect the capacities of a given freeway. Also, the group coordination is restricted by queue override policy, which may limit the effectiveness of the incremental coordination scheme on managing mainline congestion.

II. 3 California Metering System

II.3.1 Overview of Current Metering System in Los Angeles area (November, 1999)

The ramp metering system in the Los Angeles area freeway network consists of approximately 2500 meters, which have been managed by the CalTrans District 7 traffic management center. The current system, as of November 1999, employs local ‘time of day’ control with traffic-responsive turn on/off and queue override procedures. Figure 2.4 shows the typical layout of the detectors in the LA area freeway metering system, which is scheduled to switch to the SWARM algorithm in the near future. The general features of the current metering system are as follows:

- Local ‘Time of Day’ control with “temporary Green Ball operation”
- Allows two-three vehicles per green. No yellow signal (only Red + Green).
- Operator can predetermine up to 40 rates for each meter depending on time of day (Lowest :3 vehs/min, Highest: 15 vehs/min).
Figure 2.4  Typical detector layout in the Los Angeles area freeway ramps

Figure 2.5  Sequential upward coordination scheme of SWARM
• When mainline detection immediate upstream of an onramp falls below preset Volume and Occupancy thresholds, then meter signal turns to “Green Ball”, i.e., solid green, until the measured mainline volume and occupancy values exceeds those thresholds.
• When a queue detector installed upstream on an on-ramp is occupied for “3 seconds”, which is the adjustable “time out parameter”, then the highest rate, in general 15 vehicles/min, for a ramp in question is used until no queue detection. When no more queue is detected, the TOD rate applies.
• Also, the “demand detector” does not detect any vehicle, then the meter signal turns to Red.
• Green signal stays until the first vehicle passes “passage detector” : Green time : 2-3 seconds
• Outside of predetermined Time of Day control period, if mainline one minute detection exceeds “preset volume and occupancy thresholds”, then metering automatically starts (volume thresholds. 35-40 vehicles/lane/min, Occ. : ~ 20%)
• During non-control period, meters remain ‘dark’ (no flashing yellow).
• The intersection signals adjacent to a ramp are also managed by CalTrans, except those in the City of LA, to prevent off-ramp queue from blocking mainline traffic.

**Control room operations**

• Main function: Incident detection and management
• CalTrans Incident response team, California Highway Patrol, and CalTrans Freeway Service Patrol groups work together in one area.
• Currently 2 CHP dispatchers, 2-3 incident operators, 1-2 managers, 2 CF Service dispatchers work together during peak periods.
• In the future, 4 ramp operators will be added in addition to 2 traffic analysts who are in charge of incidents detection and response.

**Incident detection**

• ‘All purpose incident detection’ software with 5 algorithms was installed and calibrated.
• The main algorithm being used was developed by Pete Payne and has the capability of self tuning.
• Before calibration, it took 5-7 minutes to detect incidents with 85% false alarm rates.
• The algorithm is still being “de-tuned” to lower false alarm rate.
- No specific figures as to the current false alarm rate or proportion of incidents detected by ‘algorithm’ were available.

**Malfunction detector identification (Failure management)**

Stage 1: (built into field 170 controller)

1) If occupancy of a detector is 50% greater than the right next detector at the same location or 95% of occupancy value is reported, then it is labeled as “suspect”.

2) If “suspect” status continues 3-4 seconds, then it is called “soft failure” and no data is collected from that detector.

Stage 2: By central computer

1) Divide a given freeway into “homogeneous segments” depending on geometry and nature of traffic

2) For each segment, collect “total average lane volume per 30 seconds” by averaging all individual detector volumes.

3) Determine “acceptable volume range” for each “total average lane volume” off line. Every 30 seconds, compare the measured “total average lane volume” with each individual detector volume. If individual detector volume does not fall in the acceptable range for that particular “total average lane volume”, then that detector is labeled as “suspect”.

**Data normalization**

Use ‘assumed’ free-flow speed to estimate “effective loop length”

- use data with low volume and one assumed ‘free-flow speed’ for a given set of detectors
- adjust measured occupancy value using adjusted “effective loop length”

**II.3.2 Metering algorithm for SWARM 1 (System Wide Adaptive Ramp Metering)**

The SWARM algorithm is currently being installed in the field by CalTrans. It divides a given freeway into multiple sections whose downstream boundaries are predetermined bottlenecks. Each bottleneck is assigned the ‘saturation density’ that is calibrated off-line with historical data. The saturation density can be same or less than ‘critical density’. At every 30
seconds, the density of a bottleneck is predicted for the next T 30-second periods using a Kalman Filter, which extends the density variation trend during the past H intervals into the future periods. If the predicted bottleneck density exceeds its saturation density, then the amount of ‘volume reduction’ for each ramp within a section is determined. The detailed procedure to update metering rates is as follows:

1) Determine “Bottlenecks” in a given freeway.
   - Currently no written systematic procedure to determine bottlenecks. Based on engineering judgement by CalTrans engineers.

2) Determine “Saturation Density” for each bottleneck
   - Saturation density could be same or less than “critical density”. It is suggested to use Off-line calibration using a quadratic equation between flow rate and density.

3) Every 30 seconds, forecast the density of a bottleneck for next Tcrit periods using a Kalman Filter,
   \[ k_j(t+1) = k_j(t) + b(t) + w_t \]
   \[ x(t) = k(t) + v_t \]

(1) at time t, perform simple linear regression with the actual data during past h intervals,
(2) use observed density values and the linear slopes to seed a Kalman Filter from t-h to t,
(3) use forecasted values by the Kalman Filter for t+1 as observation values at t+1 and continue forecasting until t+Tcrit.

Figure 2.6  Bottleneck density prediction procedure
4) If forecasted bottleneck density exceeds “saturation density”, then determine “volume reduction” for each ramp within a “section” as follows:

- Required bottleneck density = (Current density) – (Forecasted density – saturation density)/Tcrit
- Needed Volume Reduction at the detector station upstream of a meter = VR = (Local Density – Required Bottleneck Density)*(# of lanes) * (Distance to next downstream ramp)
- Metering rate = Current ramp volume + VR
  : VR can be + or -.
- Repeat the above process starting from the ramp immediate upstream of a bottleneck until the furthest upstream ramp within a section.
- If VR needs to be done for ramps upstream section, then use “propagation factor” to determine the amount of volume reduction at upstream sections. “Propagation factor” is an input parameter that can be adjusted by operator.
- The above “upward adjustment procedure” was the main concept of “Central Override Ramp Metering (CORM)” developed by CalTrans staff, but CORM was never implemented in the field.

* The details of the above procedure will be finalized after field trial and fine tuning.

5) Repeat the above “Forecasting” and “Volume Reduction” process every 30 seconds, i.e., every 30 seconds, predict the bottleneck density for next Tcrit intervals and determine new VRs for each ramp.

The above procedure is repeated starting from the ramp immediate upstream of a bottleneck until the furthest upstream ramp within a section. Figure 2.7 illustrates the upward coordination scheme of the SWARM algorithm. If the ‘volume reduction’ needs to be done for the ramps in the upstream section, then a ‘propagation factor’, which is an operator-adjustable parameter, is used to determine the amount of volume reduction at upstream sections. This upward adjustment procedure with ‘prediction’ and ‘volume reduction’ process is repeated every 30 seconds for all the ramps in a section (15-17).

As discussed above, the SWARM algorithm employs the ‘prediction’ of future density at pre-defined bottlenecks and estimation of local density in real time. Therefore, its performance
Figure 2.7  Sequential upward coordination scheme of SWARM
heavily depends on the reliability of sensors as well as the accuracy of prediction. The field test results of SWARM have not been available yet.

II.4 Virginia Metering System

II.4.1 System overview

The Virginia metering system, operated by Smart Traffic Center, Virginia Department of Transportation, consists of 26 meters on the I-395 and I-66 freeways in Washington, D.C. area. The metering algorithm adopts a centralized, coordinated scheme that is based on predicted link volume and pre-determined link capacity values (4). The general features of the Virginia system are as follows;

- Meter rate is updated every 1 minute with 10 second data collection.
- Most meters release “Two cars per Green” => Two lanes have same signal.
- “Queue dump mode” starts when Occupancy value from Queue Detector exceeds 25%. In the Queue dump mode, a meter is either turned off or a predefined maximum rate is applied until the occupancy measurements become below the threshold.
- Meter Turn On/Off procedure
  If Measured link input volume exceeds preset threshold, then start metering.
  Also, turn off meters when link input volume becomes lower than threshold.
  (No requirement on time duration)
- Currently Smart Traffic Center management system software, including metering control software, is being upgraded by Lockheed Martin (OS: Unix).
  - New system is expected to start operation from November 1, 1999.
  - Metering rates will be updated every 10 seconds (currently 1 min)

II.4.2 Metering algorithm

The metering algorithm of the Virginia system adopts a link-based, section-wide coordination approach that determines metering rate as the difference between the predicted link demand and estimated link capacity every 1 minute. As illustrated in Figure 2.9, a link is defined as the mainline segment between two consecutive entrance ramps and a section can have up to 10 links. The basic features of the Virginia algorithm are as follows:
- At each time interval, calculate “Permissible Link volume (RDL)” and “Predicted Link volume (PRD)” for each link in a metering zone.
- Each ramp has Minimum (200-250 veh/hr) and Maximum rates, which are predetermined.
- Maximum rate is applied whenever Queue Dump Mode is activated.
- Metering rate is the difference between “Permissible” and “Predicted” link volumes subject to Queue and Minimum rate conditions.
- The metering algorithm in general results in more restrictive rates at downstream ramps to ‘fill’ the roadway.
- For more equal distribution of ramp delays across the ramps in a metering section, careful determination of Minimum Rates is needed.

To determine metering rates of a control section, the maximum permissible volume for each link, defined as the maximum volume that will not saturate the immediate downstream link, is first calculated as follows:

\[ RDL(n) = \min \{ Q(n), \ F(n) \ C(n), \ [F(n) \ CC(n) - EQV(n) \ RL(n)]/ p(n) \} \]

where,

- \( RDL(n) \): maximum permissible volume on link \( n \),
- \( Q(n) = [RDL(n) - RL(n)]/ p(n+1) \)
- \( RL(n) \): minimum metering rate for the on-ramp on link \( n \).
- \( p(n) \): fraction of volume remaining on the mainline after vehicles have exited at the link \( n \) off-ramp.
- \( F(n) \): desired level of service coefficient on link \( n \) (constant),
- \( C(n) \): estimated link capacity on link \( n \) (constant), to limit volume at some margin below capacity,
- \( CC(n) \): estimated merging capacity on link \( n \) (constant),
- \( EQV(n) \): ramp vehicle equivalency at mainline –ramp merge area on link \( n \).
Figure 2.8  Typical layout of an entrance ramp area in Virginia metering

Figure 2.9  Configuration of links and notations in the Virginia system
For each control section, the above calculation procedure starts with the furthest downstream link and ends with the furthest upstream link. The Q(n) for the furthest link is assumed to be a constant calibrated from historical data. The metering rate of each link is then determined as the difference between maximum permissible volume and ‘predicted mainline-arrival demand’ from the immediate upstream link. The predicted demand for each link n is determined as follows:

\[ \text{PRD}(n+1) = \max \left[ \text{PL}(n+1), \text{PL}(n) + \text{RRVOL}(n) - \text{QE}(n+1) \right] \]

where, \(\text{PRD}(n) = \text{predicted arrival demand on link } n\),

\(\text{PL}(n)\): measured mainline volume on link \(n\) (downstream of exit ramp) during previous time interval,

\(\text{RRVOL}(n)\): measured on-ramp volume at the entrance ramp on link \(n\) during previous time interval,

\(\text{QE}(n)\): predicted exit volume at the exit ramp on link \(n\) (currently measured value during previous time interval is used as the predicted exit demand).

The prediction of each link demand is performed from the furthest upstream link to the furthest downstream link in a control section. Finally, the metering rate for link \(n\), \(\text{RC}(n)\), is determined by

\[ \text{RC}(n) = \min \left\{ \left[ \text{RD}L(n) - \text{PRD}(n) \right], \left[ \text{F}(n) \text{ CC}(n) - \text{PRD}(n) \right]/ \text{EQV}(n) \right\} \]

The metering rate calculation starts with the furthest upstream link and ends with the furthest downstream link in a section. Figure 2.10 illustrates the calculation sequence of both prediction of link demand and estimation of link capacity. Currently fixed values for link and merging capacities are used in the Virginia system. In case of detector malfunction, historical values are used as default.

The ‘Queue dump mode’ starts when the occupancy value from a queue detector exceeds a predefined threshold. When the queue dump mode is activated, metering rate is increased at successive one-minute update periods until the rate reaches the upper limit of “dump” rate or queue detector occupancy becomes below threshold (13).

As reviewed above, the Virginia algorithm also adopts a strong queue override policy, which could severely restrict the effectiveness of the sequential link-coordination scheme. The effectiveness of the algorithm may be further affected by the accuracy of the link and merging capacities that are necessary to determine the maximum permissible volume for each link.
Figure 2.10 Link-based sequential coordination scheme of Virginia algorithm
II.5 Seattle Metering System

II.5.1 System overview

The Seattle metering system, consisting of 75-100 meters and covering 75-80% of the metro freeway network with 280 CCTV cameras, has recently converted to the Fuzzy logic-based metering from the previous Bottleneck algorithm. Currently the metering rates are calculated and updated every 20 seconds using the past one-minute volume/occupancy/speed data collected from the loop detectors, which are installed at each lane for every ¼ - ½ mile on mainlines. Approximately 25% of the loops installed are double loops that can directly measure speed.

Figure 2.11 Typical layout of Entrance Ramp Area in Seattle

Figure 2.11 shows a typical entrance ramp area in the Seattle system that employs a queue override procedure with the queue detectors, which are sometimes located at turn-pockets at an adjacent intersection as well as on ramps. The ramp queue override procedure is built into the metering algorithm and tries to prevent the excessive queue from spilling back to surface street (1). In this section, both previous Bottleneck and new Fuzzy metering algorithms are described in detail.
**Meter turn on/off procedure**

All the ramp meters in the Seattle system are turned on or off by a human operator manually depending on the ‘congestion condition’ displayed on the ‘Flow Map’, which shows the ‘congestion level’ for each section with different colors every 20 seconds using volume, occupancy and speed data. For example, the occupancy-based color scheme includes,

- Green (Free flowing <16%),
- Yellow (Moderate, 16-22%),
- Red (Heavy) and Black (Stop and Go).

If traffic condition at a ‘historical bottleneck’ area changes from Green to ‘Yellow’, for two-three consecutive 20-second time intervals, then the operator starts a group of meters associated with that bottleneck section. Also those meters are turned off when congestion level changes from Yellow to Green for two to three consecutive time intervals. The basic concept in determining ‘turn-on’ condition is that ‘metering would be most effective before congestion develops’. Further, ‘some times when mainline traffic is very congested, meters could be turned off. No value in metering under such conditions’ (1).

**Control Room Operations**

Personnel: Manger, 2 Floor engineers, 4 Floor operators (mostly student interns, 10-20 hrs/wk)

Peak periods: At least 2 people on the floor (1 Metering, 1 Incident response)

Off-peak: At least one person.

Operating periods: Weekdays 5:30a.m. – 7:00p.m.

Weekends: 9:00a.m.- 6:00p.m.

**II.5.2 Bottleneck Metering Algorithm (1,2)**

The original Bottleneck algorithm was developed in late 1970s by a consultant group headed by Dr. Atholl. Initially, a linear programming approach was proposed by the consultant, but it was redirected to the “process-control” algorithm by WSDOT. The main reason not to use the linear programming, i.e., optimization, approach was the difficulty in estimating Origin/Destination demand data and the capacity values that change dynamically through time depending on weather and other conditions.
In the Bottleneck algorithm mode, the system calculates Local and Bottleneck rates for each ramp every 20 seconds and select more restrictive rate, which is further adjusted with ramp queue conditions. The rest of this section includes the detailed description of the Bottleneck algorithm based on the results from the meeting with the operator and the review of the literature published to date (1,2).

1) Local metering algorithm

Use a predetermined occupancy-rate selection curve, which uses the occupancy measurements form a immediate upstream mainline detection. An example selection curve is defined with 5 points as follows:

\[ \leq 15\% \text{, } 17 \text{ veh/min}, (17\%, 15), (19\%, 12), (21\%, 9), (23\%, 7) \]

The occupancy-rate selection curve is determined and adjusted with the field data and operators’ judgements.

2) Bottleneck algorithm

(1) Divide a corridor into “sections”, defined as the area between two mainline detector stations.

(2) Determine “Influence area” for each section, i.e., upstream on-ramps that will affect the given section. (Historical information and operator judgement)

(3) Allocate Weight Factors for each ramp in each Influence area: 0 – 100

Based on operator judgement and historical information. No written systematic procedure.

(4) For each section, determine Occupancy threshold for downstream detector station to determine if a given section is “near” capacity: Usually 18%
(5) In real time, first check for each section if Downstream Occ >= Othreshold, if no, goes to next section.

If yes, calculate the following quantity to determine if vehicles are being stored with a given section:

\[ SV \text{ for section } k = \text{Sum}[\text{all input volume to section } k] - \text{Sum}[\text{all output volume from } k] \]

(6) Determine rate reduction for all the ramps in section k as follows:

\[ \text{Rate reduction for ramp } j \text{ in section } k = \frac{\text{WF}j \cdot (SV)}{\text{Sum of all WFs in section } k} \]

where WFj = weight factor for ramp j for section k.

(7) Bottleneck Rate for ramp j for t+1 in section k = Rate(j,t) - \{Rate reduction(j,t) for section k\}

(8) The above calculation is repeated for all the sections that store vehicles, therefore, one ramp could have several different bottleneck rates. Select the most restrictive rate as the final Bottleneck Rate for each ramp. Further, any section can become a bottleneck section.

(9) Select more restrictive rate between Local rate and final Bottleneck rate for each ramp and apply Queue Adjustment.

3) **Queue override procedure**

1) If there are two lanes at a ramp, e.g., HOV bypass lane, each lane works separately.

2) Initial rate before queue adjustment = Designated metering rate: Minimum of Local and Bottleneck rates

3) Adjustment with Queue detection:

   If [Occupancy at Queue Detector 1 >= QueueOccLane1 (e.g., 30%)] then timer starts.
   
   if QtimerLane1 (e.g., 2 min) minutes later,
   
   if Occupancy at Queue Detector 1 >= QueueOccLane1
   
   then Metering rate = Designated rate + Qadjust1Lane1 (1 – 2 veh/min)
   
   if after QtimerLane1 (3 – 4 min) minutes, still
   
   Occupancy at Queue Detector 1 >= QueueOccLane1
   
   then Metering rate = Designated rate + Qadjust2Lane1 (4 veh/min) <= Max. Rate
   
   if at the end of Qtimer2Lane1, still
   
   Occupancy at Queue Detector 1 >= QueueOccLane1
   
   then Metering rate = original designated rate + Qadjust2Lane1 <= Max. rate
Adjustment with Advance Queue Detection

If Occupancy at any of Advance Queue detectors exceeds ADVQOCCUPANCY1 (30%) for a designated period, ADVTIMER (80 seconds), then

\[ \text{Metering rate} = \text{Designated rate} + \text{ADVQOVERRIDE1 (5 veh/m)} \leq \text{Max. Rate} \]

Usually when advance queue override mode activates, metering rate is equal to maximum rate.

Issues with the Bottleneck algorithm

- Basically “Process Control” (not optimization):
- By depending heavily on “Volume” measurements, the algorithm is very susceptible to detection error.
- Occupancy detection was more erroneous than volume.
- When a Bottleneck is detected, current Bottleneck algorithm tends to generate minimum metering rates, which creates long queues that activates Queue Override algorithm, which in turn results in maximum metering rate.
- As a result, metering rates seem to oscillate between Minimum and Maximum values. The queue size is not directly reflected in determining metering rate with the Bottleneck algorithm (1).

II.5.3 Fuzzy metering algorithm

Fuzzy control concept was initiated by the engineers at WSDOT for the following reasons (1).

- Traffic system is hard to model. Further, the difficulties in estimating roadway capacity and Origin/Destination demand values limits the effectiveness of model-based optimization approaches.
- Fuzzy control tries to emulate the way human being controls.

The development of the specific algorithm with Fuzzy logic was performed by the research group at University of Washington (3). The initial field evaluation results showed the following results:

- Fuzzy control produces marginal improvement on mainline congestion, but better management of ramp queue.
- Balances ramp queue and mainline congestion better than the Bottleneck-algorithm. Also Fuzzy control seems to have “prediction” element.
- Less susceptible to bad data or detector malfunction.
- More flexible accommodation of queue conditions.

Based on the qualitative evaluation results, all the meters in the Seattle system were expected to be converted to the Fuzzy logic by the end of 1999. The following section summarizes the current Fuzzy metering algorithm based on the literature and the meeting results with the operator and the algorithm developer (1,3).

**Fuzzy control algorithm**

The main goal of the Seattle Fuzzy metering algorithm is to integrate different aspects of control objectives into one single algorithm, i.e., merging control, bottleneck control and prevention of excessive ramp queue, by using a qualitative method. The following figure shows the typical layout of detectors used for Fuzzy metering.

![Diagram of detector layout](image)

<table>
<thead>
<tr>
<th>DO (Downstream Occupancy)</th>
<th>OC (Mainline Occupancy)</th>
<th>UO (Adjacent Upstream Occupancy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS (Downstream Speed)</td>
<td>SP (Mainline Speed)</td>
<td></td>
</tr>
</tbody>
</table>

1) **For each meter, assign following detector stations for measurements every 20 seconds.**

   Up to 20 downstream stations for measuring occupancy and speed.
   - Based on operator judgement and historical experience
   - Maximum occupancy and minimum speed will be selected and used as bottleneck data

Mainline station just upstream of ramp merge area
- Usually immediate upstream station, but can be changed by the operator.

Queue occupancy station and Advance queue occupancy station

The above detector station assignments remain same throughout metering operations.

2) **For each meter, develop Fuzzy classes, membership function**

Fuzzy classes for occupancy/speed and metering rate:
VS (Very Small), S (Small), M (Medium), B (Big), VB (Very Big)

Membership function: quantifies the “degree of membership for each class for a given ‘crisp’ variable. The following figure illustrates one example membership function for an occupancy class consisting of Isosceles triangles with a base of $2\beta_i$ and unitary height.

3) Estimation of membership degree of each measured value

In the above figure, an example membership function for S class:

\[ f_i(x) = \begin{cases} 
(x - C_i + \beta_i) / \beta_i & \text{for } C_i - \beta_i < x < C_i \\
-(x - C_i - \beta_i) / \beta_i & \text{for } C_i < x < C_i + \beta_i 
\end{cases} \]

where $C_i$: centroid of class $i$ (e.g., 0.25 for S class)

$f_i(x)$: degree of actuation for a scaled crisp variable $x$.

Scaling equation to normalize, i.e., to convert crisp occupancy or speed values from (LL, HL) range to (0,1) range:

\[ \text{scaled crisp variable} = \frac{(\text{crisp variable})}{(HL - LL)} \cdot \frac{1}{(HL - LL)} 
\]

For each meter and each quantity to be measured, i.e., occupancy and speed, operator sets HL (high limit) and LL (low limit). Then the above equation normalizes real measured value on a 0-1 scale. The normalized value goes to membership function and the membership degree of each class for a given measured value is estimated.
4) Develop Fuzzy rules

The next step is to develop a set of Fuzzy rules that link each measurement to metering rate determination. An example Fuzzy rule set is shown as follows:

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Weight</th>
<th>Rule Premise</th>
<th>Rule Outcome for Meter Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>LOC_ Very Big</td>
<td>Very Small</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>LOC_ Big</td>
<td>Small</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>LOC_ Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>LOC_ Small</td>
<td>Big</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>LOC_ Very Small</td>
<td>Very Big</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>LS_ Very Small &amp; LOC_ Very Big</td>
<td>Very Small</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>LS_ Small</td>
<td>Small</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>LS_ Big</td>
<td>Big</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>LS_ Very Big &amp; LOC_ Very Small</td>
<td>Very Big</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>DS_ Very Small &amp; DOC_ Very Big</td>
<td>Very Small</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>QO_ Very Big</td>
<td>Very Big</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>AQO_ Very Big</td>
<td>Very Big</td>
</tr>
</tbody>
</table>

- Source: Taylor, et. al. (10-12)

LOC: Local Occupancy
LS: Local Speed
DS: Downstream Speed
DOC: Downstream Occupancy
QO: Queue Occupancy
AQO: Advance Queue Occupancy

**Interpretation of rules**

Rule 1: If the adjacent mainline occupancy (OC) is Very Big (VB), then the metering rate is Very Small(VS). If the very big fuzzy class of OC is true to a degree of 0.2, then the metering rate is very small to a degree of 0.2.

Rule 2: If the adjacent mainline occupancy (OC) is Big (B), then the metering rate is Small(S). If the Big fuzzy class of the mainline occupancy is true to a degree of 0.6, then the metering rate is Small to a degree of 0.6.
5) Defuzzification process (example)

a) First for each measured value, estimate its degree of each Fuzzy class;

<table>
<thead>
<tr>
<th>e.g.,</th>
<th>Crisp Value</th>
<th>VB</th>
<th>B</th>
<th>M</th>
<th>S</th>
<th>VS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>16%</td>
<td>0.2</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

b) Apply Fuzzy rules and estimate the degree of each Metering Rate Outcome

e.g., if Centroids of VS, S, M, B, VB are (0.083, 0.3, 0.5, 0.7, 0.916)

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight (W)</th>
<th>Premise</th>
<th>Metering rate outcome (I)</th>
<th>W * I</th>
<th>Ci<em>W</em>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>OC_VB</td>
<td>0.2</td>
<td>0.2 (VS)</td>
<td>0.2*0.083</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>OC_B</td>
<td>0.6</td>
<td>1.2 (S)</td>
<td>1.2*0.3</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total 1.4 0.365

c) Final Metering Rate calculation

Metering rate(0-1) = Sum(Ci*W*I)/Sum(W*I) = 0.365/1.4 = 0.261

If for a given ramp, Minimum rate = 7 veh/min and Maximum rate = 17 veh/min. then,
Final rate = 7 + (17-7) * 0.261 = 9.61 veh/min.

As reviewed above, the Fuzzy-metering algorithm being implemented in Seattle, Washington, is designed to integrate different aspects of control objectives, i.e., merging control, bottleneck control and prevention of excessive ramp queue, into one single algorithm by using a qualitative method similar to human reasoning. It determines the metering rate of an individual ramp every 20 seconds using a set of fuzzy rules and classes specific to each ramp. The parameters in the current algorithm, such as membership functions and rule weights, have been determined through real time tuning process (10-12). The Fuzzy-metering algorithm does not require the estimation of link capacities or traffic demand in real time. Further, as Figure 2.12 shows, the coordination of multiple ramps is implicitly incorporated into the fuzzy metering
process by sharing common set of data in determining individual metering rates. The capability to change the weights of the fuzzy rules also provides flexibility in adjusting the system performance in real time. While the simplicity of the fuzzy approach presents an alternative to conventional model-based control, the tuning or calibration of its parameters for operational traffic conditions becomes a critical issue for the effectiveness of the fuzzy control.

II.6 San Diego Metering System

II.6.1 System overview

San Diego metering system adopts a local responsive metering scheme, but the thresholds for each local control are determined from a section-wide bottleneck flow optimization process. In particular, the San Diego system does not employ a ramp-queue override policy regardless of the size of ramp queues. The general features of the system include (9,10):

- 250 meters (4 freeway to freeway meters) with 6 CCTV cameras
- Allows two car/green release depending on rate setting.
- No HOV by-pass allowed.
- No Queue override (Many ramps have long queues during peak periods).
- Control Center does not have “Video Wall”, whose value is not appreciated very much by San Diego TMC staff.
- Traffic Operators, Patrol dispatchers and Maintenance Operators are working in the same Control room. They have frequent formal/informal interactions to promote cooperative working environment.
- Computer-Aided Dispatch system is being used.
- Incident detection is mostly done with reports from drivers by cellular phones.
- Metering operation is completely done by computer without the intervention of human operators.
- No coordination with adjacent intersection signals.
Diagram showing data sharing scheme of current Fuzzy algorithm in determining individual metering.

- Detector station
- Detection data flow
- \( M_i \) = Metering rate for ramp \( R_i \)

Figure 2.12 Data sharing scheme of current Fuzzy algorithm in determining individual metering.
II.6.2 Description of Local Responsive Algorithm (9,10)

The San Diego algorithm uses immediate upstream detection on the mainline for each ramp, whose typical layout of detectors is as follows.

In San Diego,

- Metering rate is updated every 30 seconds using 1 minute data
  - Exponential smoothing of last 6 minutes’ data: \( V_{t+1} = \alpha V_t + (1-\alpha) V_{t-1} \)
- Each meter has predetermined 15 rate levels and \( \Delta V \) and \( \Delta Oc \).
  - Minimum Rate = 85% of Average un-metered rate.

For one lane ramp,

1 car/green: Min cycle = 6 secs, Max. cycle = 15 secs.
  Green time = Min. 1.4 sec to Max (until a vehicle hits passage detector)
  No yellow signal.
2 car/green: Min cycle = 7 secs, Max. cycle = 15 secs.
  Green time = Min. 3.2 secs to Max (until second car goes through yellow)
  Yellow = 2.2 secs.

\( \Delta V \) and \( \Delta Oc \) = Volume and Occupancy increments to change rates, i.e., go to next rate
  if \( V_t \geq V_{t-1} + \Delta V \), or \( O_t \geq O_{t-1} + \Delta Oc \)

Each controller stores Minimum/Maximum rates and (\( \Delta V \) and \( \Delta Oc \)).

In real time, Metering Rates between Minimum and Maximum values are calculated with pre-determined thresholds, i.e., \( \Delta V \) and \( \Delta Oc \). Metering Period consists of Start-Transition, Forced-metering and Ending-transition intervals.

**Metering Start/End Transition periods:**

- Meter starts with Solid Green at the starting time of a transition period and remains green until the measured mainline vol/occ warrantes metering.
• During Ending Transition period, when Ending condition is met, meter signal turns to Solid Resting Green until the end of a End Transition Period.
• Meter signal remains dark during no-control period.

**Meter Starting/Ending algorithm (automatic)**
• Each meter has a pair of 1 minute and 3 minute Volume/Occupancy thresholds
• During start/end transition periods, measure previous 1 minute and 3 minute volume/occupancy data.
• If measured mainline data meets both 1 minute and 3 minute Volume/Occupancy thresholds, then automatically start/end metering.
• 3 minute thresholds have lower values than 1 minute ones.
• Those thresholds are similar to the thresholds for Rate 1.

**Off-line procedure for determination of Local metering thresholds**

1) Divide whole freeway into “Control Segments”, whose downstream boundaries are Bottlenecks.

![Diagram of freeway segments and bottlenecks](image)

2) Bottleneck criteria : Geometry and Traffic Data
   No written procedure, Based on engineering judgement.

3) Determine “Flow Profile” at each Bottleneck
   Use every Thursday data (Vol, Occ. Estimated speed)

![Diagram of flow profile](image)
Determine Target Flow Rate at Bottleneck: $Q_T$

Engineering judgement, e.g., 95% of Operational Capacity, which can be maintained over a significant period of time (90 minutes or so) for nine out of ten days that are free of both incidents and inclement weather.

4) Determine Most Restrictive Metering Rate for each ramp
   - Equalization of ramp queue delays,
   - Spill-back from ramp queue to local streets
   - Other factors,
   - Usually 15% below of un-metered discharge rate

5) Determine Least Restrictive Metering Rate for each ramp.

6) Mainline Flow Rate, at Detector J, which should cause the Most Restrictive Rate:
   
   $$= [\text{Bottleneck Target Flow Rate } Q_T - \text{Most Restrictive Meter Rate at Ramp J}]$$

   where, $J = \text{Detector station immediate upstream of Bottleneck}$

7) Mainline Flow Rate, at Detector J, which should cause the Least Restrictive Rate:

   $$= [\text{Bottleneck Target Flow Rate } Q_T - \text{Least Restrictive Meter Rate at Ramp J}]$$

   where, $J = \text{Detector station immediate upstream of Bottleneck}$

8) Volume control determines interim rates, i.e., rate level 2 – 14, in a linear scale.

9) Determine Occupancy values corresponding Mainline Flow Rates at 6) and 7).

10) Determine Occupancy thresholds such a way that at the “cross-over” speed level, usually, 50 – 55 mph, Occupancy thresholds and Volume thresholds result in Equal Metering Rates for each meter.

11) Both Volume-based and Occupancy-based control produces Metering Rates every 30 seconds and More Restrictive Rate is selected for next control interval. Since Occupancy control is designed to yield more restrictive rate at speed levels lower than 50-55mph, Metering is dictated by Occupancy in congested conditions.

12) Determination of Occupancy thresholds is dependent upon field trial results and engineering judgement.
II.7 Toronto QEW-Mississauga Metering System

II.7.1 System overview

The Toronto metering system adopts an expanded local control algorithm, which uses three detector stations for each ramp, i.e., local, downstream and upstream. Figure 2.13 shows a typical layout of an entrance ramp area in the Toronto system, which consists of 10 ramps covering a 19-km section of freeway in Mississauga. The general features of the system include:

- 62 loop detector stations collecting volume/occupancy data every 30 seconds.
- Automatic rate selection algorithm using detection from three locations, i.e., local, upstream and downstream.
- Automatic Queue override when Queue detector occupancy exceeds threshold by successively decreasing rate level by one until queue detector occupancy drops off.

![Figure 2.13 Typical detector layout](image)

II.7.2 Metering Algorithm (11)

- For each ramp, assign Local, Upstream and Downstream detector stations.
- Each ramp has preset Volume/Occupancy thresholds Table (currently 5 rate levels).
- Each ramp can have up to 15 rates (currently 5 rates).
- In real time, use Occupancy measurements from Local and Downstream stations and Volume measurements from Upstream station.
- Select one rate level(code) with each measurement from Table and use the most restrictive rate for next 30 second interval.
Current operational parameters for Toronto system

Detector station Assignment

<table>
<thead>
<tr>
<th>Control Section</th>
<th>Associated Local Station</th>
<th>Associated Downstream Station</th>
<th>Associated Upstream Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>19</td>
<td>17</td>
</tr>
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<td>4</td>
<td>18</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>18</td>
<td>14</td>
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<td>6</td>
<td>15</td>
<td>18</td>
<td>14</td>
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<tr>
<td>7</td>
<td>10</td>
<td>11</td>
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<tr>
<td>8</td>
<td>7</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Volume/Occupancy Threshold Table

<table>
<thead>
<tr>
<th>Rate Code</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Station Occupancy</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>70%</td>
</tr>
<tr>
<td>Downstream Station Occupancy</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>70%</td>
</tr>
</tbody>
</table>

| Ups. st. vol.- Cont. Sect. 1 | 70 | 80 | 90 | 100 | 120 |
| Ups. st. vol.- Cont. Sect. 2 | 70 | 80 | 90 | 100 | 120 |
| Ups. st. vol.- Cont. Sect. 3 | 65 | 75 | 85 | 95  | 110 |
| Ups. st. vol.- Cont. Sect. 4 | 65 | 75 | 85 | 95  | 110 |
| Ups. st. vol.- Cont. Sect. 5 | 55 | 65 | 75 | 85  | 100 |
| Ups. st. vol.- Cont. Sect. 6 | 55 | 65 | 75 | 85  | 100 |
| Ups. st. vol.- Cont. Sect. 7 | 45 | 55 | 75 | 85  | 100 |
| Ups. st. vol.- Cont. Sect. 8 | 45 | 55 | 75 | 85  | 100 |
| Ups. st. vol.- Cont. Sect. 9 | 45 | 55 | 75 | 85  | 100 |
| Ups. st. vol.- Cont. Sect. 10 | 70 | 80 | 75 | 90  | 110 |
**Metering rate(code) Table (One set of rates for all ramps)**

<table>
<thead>
<tr>
<th>Metering Code</th>
<th>Timing Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0 second</td>
</tr>
<tr>
<td>1</td>
<td>5.0 second</td>
</tr>
<tr>
<td>2</td>
<td>6.0 second</td>
</tr>
<tr>
<td>3</td>
<td>7.5 second</td>
</tr>
<tr>
<td>4</td>
<td>10.0 second</td>
</tr>
<tr>
<td>5</td>
<td>15.0 second</td>
</tr>
<tr>
<td>6</td>
<td>15.0 second</td>
</tr>
<tr>
<td>7</td>
<td>15.0 second</td>
</tr>
<tr>
<td>8</td>
<td>15.0 second</td>
</tr>
<tr>
<td>9</td>
<td>15.0 second</td>
</tr>
<tr>
<td>10</td>
<td>15.0 second</td>
</tr>
<tr>
<td>11</td>
<td>15.0 second</td>
</tr>
<tr>
<td>12</td>
<td>15.0 second</td>
</tr>
<tr>
<td>13</td>
<td>15.0 second</td>
</tr>
<tr>
<td>14</td>
<td>15.0 second</td>
</tr>
<tr>
<td>15</td>
<td>15.0 second</td>
</tr>
<tr>
<td>16</td>
<td>Activating the Autoramp</td>
</tr>
<tr>
<td></td>
<td>Metering Control</td>
</tr>
</tbody>
</table>

**Metering period**

<table>
<thead>
<tr>
<th>Schedule No.</th>
<th>Time</th>
<th>Control Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06:00</td>
<td>1 (Turn-On transition)</td>
</tr>
<tr>
<td>2</td>
<td>06:30</td>
<td>2 (Metering period)</td>
</tr>
<tr>
<td>3</td>
<td>08:30</td>
<td>3 (Turn Off transition)</td>
</tr>
<tr>
<td>4</td>
<td>10:00</td>
<td>0 (Off: Permanent Green)</td>
</tr>
</tbody>
</table>

*Turn On/Off threshold: the Lowest volume or occupancy threshold.*
II.8 Minnesota Metering Algorithm

The Minnesota algorithm, developed by the engineers at the Minnesota Department of Transportation, adopts a combined strategy of volume-based, zone-wide coordination and occupancy-based individual ramp control (15). Each meter has six pre-allocated rates and one rate is selected every 30 seconds by comparing two rates from volume and occupancy control. In the volume-based zone control, a freeway is divided into multiple zones whose downstream boundaries are known bottlenecks (Figure 2.14).

Let

- $Mt$: Sum of Metering rates for all the ramps metered during time interval $t$ within zone $i$
- $Ft$: Sum of freeway to freeway metering rates during $t$ within zone $i$
- $Ut$: Sum of entering volume from all un-metered ramps during $t$ within zone $i$
- $Xt$: Sum of exit ramp volume for all the exit ramps during $t$ within zone $i$
- $At$: Upstream boundary measured volume during $t$
- $Bi$: Capacity of bottleneck $B$ of zone $i$

Then applying the flow conservation principle to the zone $i$ results in the following flow balance equation:

$$(Mt + Ft)i = Bi - At - Ut + Xt + St$$

where, $St = "Zone Capacity" - \Sigma[(Oc_i) * \alpha_i * (number of lanes at i)]$

Zone capacity = zone-specific input parameter indicating the number of vehicles in a zone when it is "full" with vehicles.

$l = mainline$ detector station within a zone between upstream and downstream boundaries, i.e., not including both end stations.

$Oc_i = Occupancy measurements from detector l during t interval$

$\alpha_i = Conversion parameter for detector l (input parameter with a default value of 1.1)$

$Bi = Bottleneck capacity (input parameter for zone boundary detector station)$

The zone-based metering control tries to balance the flow in each zone by determining the total input to zone $i$, i.e., $(M + F)i$, that equals to the right-hand-side of the above equation. The volume thresholds for each zone represent the sum of the metering rates for all the meters in a zone at each rate level. In real time, the volume thresholds are compared with the measured value of the above equation and a zone-wide rate level is selected. This volume-based rate is then compared with the rate determined from the occupancy control, which uses the maximum
Figure 2.14 Combined strategy of zone-based metering scheme of Minnesota algorithm
occupancy value from several pre-assigned downstream detector stations. Table 1 shows the current volume and occupancy thresholds used in the Minnesota algorithm (15).

As described above, the Minnesota algorithm determines the metering rate of an individual ramp by reflecting immediate downstream bottleneck flow level and the traffic conditions of further downstream locations. Further, it does not employ queue override policy in determining metering rates in real time. The key parameters that affect the system performance include the estimates of bottleneck capacities, target demands and occupancy thresholds for each ramp. Reliable detection at key locations, i.e., boundaries of each metering zone and entrance/exit ramps, is also required.

Table 1. Current volume/occupancy thresholds for Minnesota algorithm

<table>
<thead>
<tr>
<th>Measured value of $V_i$</th>
<th>Rate Level</th>
<th>Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_i &gt; 1.4 M_T + 1.2 F_T$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>$1.4 M_T + 1.2 F_T &gt;= V_i &gt; 1.2 M_T + 1.1 F_T$</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$1.2 M_T + 1.1 F_T &gt;= V_i &gt; 1.0 M_T + 1.02 F_T$</td>
<td>3</td>
<td>&lt;16%</td>
</tr>
<tr>
<td>$1.0 M_T + 1.02 F_T &gt;= V_i &gt; 0.8 M_T + 0.9 F_T$</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>$0.8 M_T + 0.9 F_T &gt;= V_i &gt; 0.6 M_T + 0.8 F_T$</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>$V_i &lt;= 0.6 M_T + 0.8 F_T$</td>
<td>6</td>
<td>&gt;40</td>
</tr>
</tbody>
</table>

where, $V_i = B_i - A_t - U_t + X_t + S_t$

$M_T =$ sum of target volumes for normal ramps,

$F_T =$ sum of target volumes for freeway to freeway ramps.
III. COMPARATIVE ANALYSIS OF SELECTED METERING ALGORITHMS USING MACROSCOPIC SIMULATION

III.1 Introduction

As reviewed in the previous section, operational metering algorithms for coordinated control can be classified into three categories, i.e., Denver’s incremental group coordination approach, the section-wide explicit coordination being employed by California, Virginia and Minnesota, and the Fuzzy-logic based implicit coordination approach adopted in Seattle. In this research, the performance patterns of three different coordinated metering strategies were analyzed by simulating each algorithm under the same geometry and traffic conditions. The selected algorithms are the incremental coordination approach of Denver, the zone-wide control method of Minnesota and the Fuzzy-metering algorithm being implemented in Seattle. For this analysis, a 16-mile section of the 169 freeway in the metro area of the Twin Cities, Minnesota, is selected as shown in Figure 3.1. This section, which has 28 entrance and 28 exit ramps with 30 mainline loop-detector stations, has been metered by the Minnesota algorithm, which divides the whole section into four metering zones. Further, each meter has 6 rates pre-determined from the historical average demand. Also up to 9 downstream detector stations are assigned to each meter to measure the occupancy values. Each entrance ramp is equipped with single loop detector located right after a stop line. Figure 3.1 also shows the location of individual detectors and detector stations as well as the boundaries of each metering zone currently used in the Minnesota algorithm. In this analysis, the current metering-zone structure and 6 rates for each meter in the Minnesota algorithm are used for the Denver algorithm for its group configuration and metering rates. Further, the occupancy stations assigned to each meter in the Minnesota algorithm were used as the downstream bottleneck stations in the Fuzzy metering. A common metering-period, i.e., 2:30p.m. to 7:30p.m., was used for the simulation of each algorithm, while the whole simulation period covers from 2:00p.m. until 8:00p.m.

The simulation model used in this analysis, called Kronos, is based on the macroscopic continuum approach and estimates the flow rate, density and speed of every 100 ft segment every one second by explicitly modeling the behavior of the interrupted flows, such as merging, diverging and weaving. The description of the traffic models in Kronos and the detailed results of model testing can be found in the literature (19-23). Due to the macroscopic nature of the
Figure 3.1 Geometry of the sample freeway
simulation model used in this research, the following indices are adopted as the measures of effectiveness (MOE) for the performance of each algorithm:

- Total vehicle hours (mainline and ramp): \( \sum_i \sum_t [K_i(t) \times \Delta x] \times \Delta t \)
- Total mainline congested vehicle hours:
- Average ramp vehicle hours:
- Total mainline vehicle miles: \( \sum_i \sum_t [K_i(t) \times \Delta x] \times [U_i(t) \times \Delta t] \)

where, \( K_i(t), U_i(t) \) = density, speed of segment i at time t,
\[ \Delta x = \text{length of segment i (100 ft)}, \quad \Delta t = \text{simulation time step (1 second)}. \]

As indicated in the above formula, with the same number of vehicles on the roadway, higher speed conditions would result in higher vehicle miles with less amount of total vehicle hours. Further, an index called 'congested vehicle hours', which represent the vehicle hours of the traffic flow whose speed level is below 45 mile/hr, was used in this analysis to capture the amount of congestion on the mainline resulting from each strategy.

The traffic data for this research were collected from all the detectors in the sample freeway section for two six-hour periods, i.e., 2:00p.m. – 8:00p.m., on two Tuesdays in October 2000. Using the traffic data from the sample freeway, the simulation model is first calibrated for the sample freeway section by adjusting the flow-density relationships of the sample freeway section to minimize the differences between the measured and simulated volumes at the detector locations located on the mainline. Figure 3.2 shows the comparison results between simulated and measured volume data at one detector station located in the middle of the sample freeway section. The 5-minute volume comparison between measured and estimated data at the 30 mainline detector stations over two six-hour periods resulted in approximately 12% of the overall mean percentage difference, while the mean percentage difference at individual detector stations ranged from 6% to 27%.

In this research the performance patterns of the selected algorithms were analyzed by conducting the sensitivity analysis of each metering strategy with respect to the changes in the key parameters under the same geometry and demand condition. The rest of this chapter describes the simulation results of each algorithm.
Figure 3.2 5-minute Volume comparison results at Station 766 (Day 1)
III.2 Simulation of Denver Incremental Coordination algorithm

The Denver metering algorithm uses the incremental coordination approach with on-line identification of critical ramps. It requires ‘grouping’ of the meters on a given freeway and pre-determined six rates for each meter with volume/occupancy thresholds. In this analysis, the current four metering zones and the six-rate per ramp structure in the sample freeway, which has been metered by the Minnesota system, are used as the groups and the rate structure for the Denver algorithm that employs a queue override scheme with pre-defined occupancy thresholds. The simulation analysis focused on the examination of the effects of variations in the local volume/occupancy and the queue occupancy thresholds on the system performance. The 5-minute volume data collected from the entrance/exit ramps in the sample freeway section were used as the demand data. First, the effects of volume threshold changes on the system performance were analyzed by simulating the sample freeway with different sets of volume thresholds, while keeping the occupancy thresholds same as the current default values in the Denver system, as illustrated in Figure 3.3. Further, the queue override policy was not activated for this set of simulation, so that the effects of volume threshold changes can be clearly identified.

The simulation results of different volume threshold options without employing the queue override policy are shown in Figures 3.5 and 3.6, which indicates the continuous increase of the mainline vehicle hours as the volume thresholds increase. However, as expected, too high volume thresholds resulted in the reduction of the mainline vehicle miles and the increase of the congested vehicle hours. Next, different sets of queue occupancy thresholds were simulated with the same volume/occupancy thresholds, which showed the best results in Figures 3.5 and 3.6, to analyze the effects of queue control policies on the system performance. Figures 3.7 and 3.8 show the simulation results indicating significant deterioration of the system performance as the queue occupancy thresholds increase, i.e., as queue control becomes more aggressive. Further simulation with the 2nd day data also resulted in the similar performance patterns of the Denver algorithm in terms of its sensitivity with respect to the changes in volume and queue occupancy thresholds. The simulation results with different sets of occupancy thresholds with the same set of volume thresholds did not produce significant changes in the system performance. It can be noted that the effectiveness of the incremental coordination approach can be substantially limited by the current aggressive queue control scheme, which can override group coordination.
Figure 3.3  Volume threshold options for Denver metering algorithm

Figure 3.4  Queue Occupancy threshold options
Figure 3.5  Effects of volume thresholds on Denver algorithm performance (Day 1)

Figure 3.6  Effects of volume thresholds on Denver algorithm performance (Day 2)
Figure 3.7. Effects of Queue occupancy thresholds on Denver algorithm performance (Day 1, Volume Threshold: 1875-2275)

Figure 3.8. Effects of Queue occupancy thresholds on Denver algorithm performance (Day 2: Volume threshold: 1875-2275)
Figure 3.9 Performance of Denver algorithm with adjusted volume thresholds (Day 1)

Figure 3.10 Performance of Denver algorithm with adjusted volume thresholds (Day 2)
Table 2. Simulation results of Denver Algorithm (Day 1)

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Mainline Veh. Hrs</th>
<th>Ramp Veh. Hrs</th>
<th>Total Veh Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Mainline Veh. Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol(1575-1975)NoQ</td>
<td>5001</td>
<td>1863</td>
<td>6864</td>
<td>55.46</td>
<td>312009</td>
</tr>
<tr>
<td>Vol(1675-2075)NoQ</td>
<td>5009</td>
<td>1706</td>
<td>6715</td>
<td>9.92</td>
<td>313995</td>
</tr>
<tr>
<td>Vol(1775-2175)NoQ</td>
<td>5122</td>
<td>1456</td>
<td>6578</td>
<td>19.84</td>
<td>315563</td>
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<tr>
<td>Vol(1875-2275)NoQ</td>
<td>5344</td>
<td>1280</td>
<td>6624</td>
<td>111.04</td>
<td>316738</td>
</tr>
<tr>
<td>Vol(1975-2375)NoQ</td>
<td>5428</td>
<td>1143</td>
<td>6571</td>
<td>167.23</td>
<td>316011</td>
</tr>
<tr>
<td>Vol(1875-2275)Q(70-30)</td>
<td>5657</td>
<td>1197</td>
<td>6854</td>
<td>355.7</td>
<td>315374</td>
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<tr>
<td>Vol(1875-2275)Q(60-20)</td>
<td>5646</td>
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<td>6808</td>
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<td>314443</td>
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<td>Vol(1875-2275)Q(40-20)</td>
<td>5649</td>
<td>1151</td>
<td>6800</td>
<td>364.35</td>
<td>314468</td>
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</table>

Table 3. Simulation results of Denver Algorithm (Day 2)

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Mainline Veh. Hrs</th>
<th>Ramp Veh. Hrs</th>
<th>Total Veh Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Mainline Veh. Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol(1575-1975)NoQ</td>
<td>4824</td>
<td>1946</td>
<td>6770</td>
<td>9.35</td>
<td>298726</td>
</tr>
<tr>
<td>Vol(1675-2075)NoQ</td>
<td>4922</td>
<td>1682</td>
<td>6604</td>
<td>14.24</td>
<td>300785</td>
</tr>
<tr>
<td>Vol(1775-2175)NoQ</td>
<td>5683</td>
<td>1393</td>
<td>7076</td>
<td>548.76</td>
<td>304726</td>
</tr>
<tr>
<td>Vol(1875-2275)NoQ</td>
<td>5790</td>
<td>1230</td>
<td>7020</td>
<td>623.95</td>
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</tr>
<tr>
<td>Vol(1975-2375)NoQ</td>
<td>5807</td>
<td>1157</td>
<td>6964</td>
<td>638.98</td>
<td>304667</td>
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<tr>
<td>Vol(1875-2275)Q(70-30)</td>
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<td>1149</td>
<td>7107</td>
<td>825.59</td>
<td>301606</td>
</tr>
<tr>
<td>Vol(1875-2275)Q(60-20)</td>
<td>5963</td>
<td>1138</td>
<td>7101</td>
<td>829.67</td>
<td>301593</td>
</tr>
<tr>
<td>Vol(1875-2275)Q(40-20)</td>
<td>5966</td>
<td>1127</td>
<td>7093</td>
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</table>
III.3 Simulation of Fuzzy metering algorithm

The Fuzzy metering simulation module developed in this research uses the same fuzzy classes and membership functions as in the current Seattle algorithm with the same set of the fuzzy rules (12). Further, the current minimum and maximum rates for each meter used in the Minnesota algorithm are applied to the Fuzzy metering. The same set of the downstream occupancy stations used in the Minnesota system for each meter is also assigned to each ramp for the Fuzzy algorithm. The mainline stations located immediately upstream of each ramp are used as local stations, which measure occupancy and speed data every 20 seconds. In addition, two detector stations are installed at each ramp as the queue and advance queue detector stations.

In this research, the performance variation of the Fuzzy algorithm with respect to the changes in the rule weights is analyzed using simulation. In particular, the weights of the following four rules, which have the largest weights in the current rule set, were varied and the effects of each rule on the system performance were analyzed.

Rule 1 (2.5): Local Occupancy Very Big (VB), then Metering Rate is Very Small (VS),
Rule 10 (4.0): Downstream Occupancy VB and Speed VS, then Metering Rate VS,
Rule 11 (2.0): Queue Occupancy VB, then Metering Rate VB,
Rule 12 (4.0): Advance Queue Occupancy VB, then Metering Rate VB.
*(default weight)

Figures 3.11 and 3.12 show the simulation results of the Fuzzy-metering algorithm with different values of the weights of the Rule 11, i.e., the weight for queue occupancy measurements, while all other parameters remained same. It can be noted, as expected, that as the weight on the queue occupancy increases, i.e., with more emphasis on ramp queue conditions, the amount of ramp vehicle hours decreases and the mainline vehicle hours increase. However, it is interesting to note that too much weight, i.e., higher than 2.0, on the queue occupancy results in the increase of the congested vehicle hours on the mainline, thus reducing the total mainline vehicle miles. Figures 3.13 and 3.14 show the effects of different weights for the advance queue occupancy measurements, i.e., Rule 12, on the system performance, which exhibits the similar pattern, while the weight value higher than 1.0 resulted in the reduction of the mainline vehicle miles.
Figure 3.11 Effects of weight on Rule 11 (Day 1)

Figure 3.12. Effects of weight for Rule 11 (Day 2)
Figure 3.13 Effects of weight on Rule 12 (Day 1)

Figure 3.14 Effects of weight on Rule 12 (Day 2)
The simulation results with the combined weights on the queue and advance queue measurements are included in Figures 3.15 and 3.16, which show that the case with 1.0 and 2.0 resulted in the highest level of mainline vehicle miles among the simulated cases. It should be noted from the figures 3.11-3.16 that the cases with zero weight on both queue occupancy measurements consistently resulted in the least amount of congested vehicle hours in the mainline, while the difference in the total mainline vehicle miles is relatively small, i.e., 1-3%. Figures 3.17 and 3.18 show the effects of different weights of the Rule 10 with the fixed weights for Rule 11 and 12 as 1.0 and 2.0 respectively. As indicated in the figure, the highest weight on the downstream occupancy and speed measurements produced the best results in terms of the congested vehicle hours and the mainline vehicle miles.

The simulation results of the fuzzy metering show the sensitivity of the algorithm performance with respect to different values of the rule weights, which are relatively easy to be changed in real time indicating the possibility of on-line adjustment of the system performance. Further, zero weight option on queue occupancy measurements has resulted in consistently less total vehicle hours than other cases with compatible total mainline vehicle miles, indicating the potential negative effects of queue override method on congestion management.
Table 4: Simulation results of Fuzzy Algorithm (Day 1)

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Mainline Veh. Hrs</th>
<th>Ramp Veh. Hrs</th>
<th>Total Veh Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Mainline Veh. Miles</th>
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Table 5. Simulation results from Fuzzy algorithm (Day 2)

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<th>Mainline Veh. Miles</th>
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Figure 3.15. Effects of combined weights on Rule 11 and 12 (Day 1)

Figure 3.16 Effects of combined weights on Rule 11 and 12 (Day 2)
Figure 3.17. Effects of different weights on Rule 10 (Day 1, Queue weights 1,2)

Figure 3.18. Effects of different weights on Rule 10 (Day 2, Queue weights 1,2)
III.4 Simulation of Minnesota algorithm

Finally the Minnesota algorithm was simulated with the same demand data used for the other two cases for the sample freeway section. The Minnesota algorithm, which does not employ queue override scheme, combines the volume-based zone-wide control with the occupancy-based individual ramp control. Each meter has 6 rates with pre-determined volume/occupancy thresholds. The volume thresholds are zone-based and determined to maximize the flow levels at the downstream boundary of each zone, while the occupancy thresholds are used to reflect the traffic conditions at further downstream and can vary from ramp to ramp. In this simulation analysis, the performance patterns of the Minnesota algorithm with respect to the changes in the system-wide occupancy thresholds and the rate level-ranges were examined. Figure 3.19 and 3.20 show the different sets of occupancy thresholds and the rate level-range options simulated in this analysis. In Figure 3.20, RC 2 denotes the case with the first two rate levels, i.e., only rate level 1 and 2 of the current 6 rates will be applied to all the meters, while RC 6 is the current default case with all 6 rate levels. Therefore, the minimum rate level of RC 2 is 2, while that of RC 6 is 6, which is the most restrictive rate level.

The simulation results with different occupancy threshold options for two days are included in Figures 3.21 and 22. Each simulation was conducted with the same zone-based volume thresholds currently being used for the sample freeway. As indicated in these figures, high occupancy thresholds allowed more vehicles to enter the mainline and it resulted in increased mainline vehicle-hours with decreased ramp vehicle-hours. Further, it can be seen that as more vehicles enter the mainline, the mainline vehicle-miles are also increasing, but the rate of increase substantially decreases with the occupancy thresholds higher than the 13-37%, while the congested vehicle-hours on the mainline significantly increases. It can be also noted that the variation patterns of the total vehicle-hours, i.e., mainline and ramp, are consistent for two days. However, while the vehicle-miles of Day 2, which has more concentrated peak-period demand than Day 1, reaches the near-peak point with the 13-37% occupancy thresholds, the mainline vehicle-mile plot of the Day 1 shows a continuously increasing pattern as the occupancy thresholds increase beyond 13-37%.

Figures 3.23-3.24 show the simulation results with different levels of rate-range with the fixed occupancy thresholds 13-37%. It needs to be noted that, in this research, 100% driver compliance was assumed with the simulation of different levels of minimum rate metering.
Figure 3.19. Occupancy threshold options for Minnesota algorithm

Figure 3.20. Different Rate level-range options
Figure 3. 21 Simulation results with different occupancy thresholds (Day 1)
Figure 3.22 Simulation results with different occupancy thresholds (Day 2)
Figure 3.23  Effects of different minimum rate levels (Day 1)
Figure 3.24 Effects of different minimum rate levels (Day 2)
It has been observed in the field that drivers tend not to stop at the meter stop line if red time intervals are short and there are no vehicles waiting on the queue in front of him or her. The vehicle-hour figures for both days show a consistent pattern, i.e., more restrictive metering with lower minimum rate levels produced less total system vehicle-hours with reduced mainline congested vehicle-hours. The simulation results with the Day 2 show that the mainline vehicle-miles increase as the minimum rate level decreases, while the results with the Day 1 indicate that RC 3, i.e., the case with only first three rates, has the highest mainline vehicle-miles. Further examination of the density contour plots as in Figures 3.25 indicate that the traffic demand of Day 2 show highly concentrated pattern during the peak period, while Day 1 shows more distributed demand pattern than Day 2 throughout the metering period. The combination of the more distributed demand pattern and, the fact that Rate 3 is determined to be close to the average demand of each ramp in the Minnesota algorithm, could have produced the highest mainline vehicle-miles for the RC 3 case in Day 1. Figures 3.26 – 3.27 show the density contour plots resulting from the simulations with different levels of rate-range options for each day. As expected, the higher rate-level options, i.e., Rate 2 and 3, exhibit more concentrated level of congestion on the mainline during the peak-period.

Figures 3.28 and 3.30 include the simulation results with two different variations of the Minnesota algorithm, i.e., the zone-based volume control without employing occupancy thresholds and the occupancy-based control without using volume thresholds. Each case was simulated with 6 rate levels. It can be seen that the zone-based volume-only control resulted in the most restrictive metering, which stored more vehicles at the entrance ramps than the other cases during the metering period. The contour plot from the volume-only control also indicates that the simultaneous release of those stored vehicles from all the metered ramps at the end of the metering period created local congestion at the bottleneck located in the middle of the sample freeway section. Further, it is interesting to note that the occupancy-based control without volume thresholds consistently showed more distributed traffic pattern with less congested vehicle-hours on mainline than the other two cases for both days. In the occupancy-based control, the rate of a ramp meter is determined from the highest occupancy measurement from a set of pre-assigned downstream stations, which in general cover longer downstream area than the case with the zone-based volume control. While, the effectiveness of the occupancy-only
control scheme needs to be examined with different types of demand data, the desirable features of the occupancy control, i.e., moving bottleneck and longer coverage area, require further study.

The performance patterns of the Minnesota metering showed strong sensitivity in terms of the mainline vehicle miles and ramp vehicle-hours with respect to changes in the occupancy thresholds. This indicates the possibility of on-line adjustment of the system performance by changing the occupancy thresholds. Further, most cases with 6 rates produced significantly lower congested vehicle-hours in mainline with compatible mainline vehicle-miles than other algorithms. However, the ramp vehicle-hours of those 6-rate cases showed higher values than those from the Denver incremental coordination algorithm that uses a queue override policy. The simulation with different minimum rate levels showed that it is possible to reduce ramp vehicle-hours with the current Minnesota algorithm by employing faster rates, e.g., using only first two rate levels, but it would result in significantly increased mainline congested vehicle-hours and reduced mainline vehicle-miles as illustrated in Figures 3.23-3.27. Tables 6 -11 include the simulation results of the different cases with the Minnesota algorithm.

III. 4 Comparison of Performance Patterns

Figures 3.30 and 3.31 show the density contour plots from three cases selected to represent each algorithm for the purpose of comparing performance patterns. Since the time and budget limitations of this work prohibit exhaustive simulation analysis to search the best performance possible with each algorithm under the given geometry and demand conditions, the focus of this simulation analysis is limited to identify the general features and performance patterns of each algorithm. As indicated in those figures, the incremental coordination method employing queue override consistently resulted in more congestion on the mainline than the fuzzy and the Minnesota algorithms. In particular, the Minnesota algorithm that does not use a queue override scheme distributed traffic more evenly through space and time with lower congested vehicle-hours on mainline than the other algorithms. Further, both Denver incremental and Fuzzy metering algorithms performed better without ‘queue override’ or less ‘queue weights’ in terms of reducing the mainline congestion level while producing compatible mainline vehicle miles with other cases. It may indicate the negative effects of aggressive queue control in managing freeway congestion. The simulation results of the fuzzy metering also
Figure 3.25  Performance comparison of 3-Rate cases for two days
Figure 3.26  Density Contour Plots with different minimum rate levels (Day 1)
Figure 3.27  Density contour plots with different minimum rate levels (Day 2)
Figure 3.28  Density contour plots of different control approaches (Day 1)
Figure 3.29  Density Contour Plots of different control approaches (Day 2)
Figure 3.30 Performance comparison of control options in Minnesota algorithm
Table 6: Performance of Mn/DOT(zone/occupancy) Algorithm for Day 1

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Main Hrs</th>
<th>Veh. Hrs</th>
<th>Ramp Hrs</th>
<th>Veh. Hrs</th>
<th>Total Hrs</th>
<th>Veh. Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Main Veh. Miles</th>
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Table 7: Performance of Mn/DOT(occupancy) Algorithm for Day 1

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Table 8: Performance of Mn/DOT(zone) Algorithm for Day 1

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Table 9: Performance of Mn/DOT(zone/occupancy) Algorithm for Day 2

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Table 10: Performance of Mn/DOT(occupancy) Algorithm for Day 2

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<th>Veh. Hrs</th>
<th>Ramp Hrs</th>
<th>Veh. Hrs</th>
<th>Total Hrs</th>
<th>Veh. Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Main Veh. Miles</th>
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<td></td>
<td>6660</td>
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<td>Occ(16%-40%)R6</td>
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Table 11: Performance of Mn/DOT(zone) Algorithm for Day 2

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<th>Total Hrs</th>
<th>Veh. Hrs</th>
<th>Main Cong. Veh. Hrs</th>
<th>Main Veh. Miles</th>
</tr>
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<tr>
<td>R3</td>
<td>5585</td>
<td>1291</td>
<td>6876</td>
<td></td>
<td>549.98</td>
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<td>1474</td>
<td>6847</td>
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<td>355.12</td>
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<tr>
<td>R6</td>
<td>5381</td>
<td>1548</td>
<td>6929</td>
<td></td>
<td>323.43</td>
<td></td>
<td>305739</td>
<td></td>
</tr>
</tbody>
</table>
showed the strong sensitivity of the algorithm with respect to the changes in the system parameters, e.g., rule weights on queue occupancy and downstream traffic measurements.

Figures 3.35-3.41 include the 5-minute average ramp vehicle-hours at each entrance ramp resulted from three representative cases during the metering period for two days. As indicated in these figures, the Denver algorithm, adopting a queue-override policy, produced the lowest ramp vehicle-hours throughout the entire metering period. Further, the Minnesota algorithm clearly showed more number of entrance ramps with higher ramp vehicle-hours than other metering schemes, while the ramp vehicle-hour patterns of the Minnesota and Fuzzy algorithms show similar trend during less congested peak-period. It can be further noted that the ramp vehicle-hour patterns resulted from the Minnesota algorithm show significant zone to zone variations, while the ramp vehicle-hours from the Fuzzy algorithm have more ramp to ramp variations.
Incremental (Denver) Queue overr.(70-30%)  Fuzzy (Queue weights 1,2)  Minnesota Occ. (16-40%)

Figure 3.31  Performance pattern comparison (Day 1)
Incremental (Denver) Queue overr.(70-30%)
Fuzzy (Queue weights 1,2)
Minnesota Occ. (16-40%)

Figure 3.32 Performance pattern comparison (Day 2)
Figure 3.33 Performance comparison of metering algorithms
Figure 3.34 5-min average ramp vehicle-hours during peak-congested period (Day 1)

Figure 3.35 Total mainline vehicle-miles during peak-congested period (Day 1)
Figure 3.36 5-min average ramp vehicle-hours during less-congested period (Day 1)

Figure 3.37 Total mainline vehicle-miles during less-congested period (Day 1)
Figure 3.38 5-min average ramp vehicle-hours during peak-congested period (Day 2)

Figure 3.39 Total mainline vehicle-miles during peak-congested period (Day 2)
Figure 3.40  5-min average ramp vehicle-hours during less-congested period (Day 2)

Figure 3.41  Total mainline vehicle-miles during less-congested period (Day 2)
IV. DEVELOPMENT AND EVALUATION OF ALTERNATIVE STRATEGIES FOR COORDINATED RAMP METERING

IV.1 Introduction

As reviewed in the previous chapter, the operational metering algorithms for on-line coordinated control can be classified into three categories, i.e., the incremental group coordination approach being implemented in Denver, Colorado, the fuzzy logic-based implicit coordination method of the Seattle system, and the bottleneck-based section-wide control methods being employed by Minnesota, Virginia and California. The incremental coordination approach sequentially restricts the metering rates of upstream ramps by one level each time interval whenever a ramp operates at its most restrictive rate or in a queue override mode. While the simplicity of this approach appeals for real time implementation, the aggressive use of queue override policy can substantially limit the effectiveness of the coordination. In the fuzzy metering system being operated in Seattle, Washington, the coordination of multiple ramps is implicitly incorporated into the rate calculation process by sharing common set of data in determining individual metering rates. Further, the weights of the fuzzy rules can be easily changed in real time, thus providing significant flexibility in real time operations. Both incremental coordination and fuzzy metering algorithms do not require the estimation of link capacity and prediction of traffic demand. While the bottleneck-based section-wide control methods adopt explicit coordination approach to keep the flow levels at bottlenecks under their capacity, most existing coordination strategies, such as Minnesota and California, require the estimation of the link capacity or saturation density at pre-determined bottlenecks. Further, most algorithms currently in operation directly use point measurements in determining metering rates and, therefore, can be sensitive to detector malfunction.

The difficulties in estimating capacity values at bottlenecks lead to the development of non-capacity based strategies such as the incremental group coordination and the fuzzy logic-based metering. Although these methods do not explicitly require freeway link capacity in determining metering rates, the implicit and reactive nature of their coordination strategies limit the effectiveness of coordinated ramp metering. Developing a practical and reliable ramp metering strategy that can maximize the efficiency of a freeway system with available detection is of critical importance in managing congestion. The metering strategy should be able to adapt to the continuously changing traffic conditions, such as weather, incidents and detector malfunction.
In this chapter, two new metering strategies that are based on different concepts are developed and evaluated. First approach extends the conventional bottleneck-dependent, zone-based coordination approach by introducing the concept of nested-zone. As in the current Minnesota algorithm, this approach requires the estimation of the capacities at each bottleneck location. The second approach combines the conventional zone-based control concept with fuzzy-based inter-zone coordination scheme. Unlike the existing methods that are based on point measurements, this method uses a zone-wide congestion index that can be estimated using all the available detector stations in a given zone. The rest of the chapter includes the description of the new metering strategies and the testing results.

IV.2 Capacity-based Nested-Zone Metering Approach

IV.2.1 Overview of Nested-zone Metering Concept

The nested zone-based metering control is the enhanced version of the existing Minnesota algorithm, whose fixed zone structure may not effectively deal with local congestion within a zone. In this approach, each primary zone under the current Minnesota algorithm is divided to a set of sub-zones, which share the common upstream station as that of the primary zone. However, the downstream station of each sub-zone varies within a primary zone as shown in figure 4.1. The main objective of nested zone metering is to capture local congestion within a zone more efficiently than the current primary-zone based algorithm. For example if the Nested Zone 1, shown in Figure 4.1, is congested, then applying volume control to Nested Zone 1 produces more restrictive rate for Meter M1 compared to applying volume control to the primary zone. This way congestion can be tackled at the initial stage before the whole primary zone becomes congested.
Figure 4.1 Nested Zones in a primary zone
The main features of the nested zone metering are.

- For each primary zone, the nested zone structure is fixed, predetermined and depends on the configuration of mainline stations.
- Nested zones are defined to include at least one entrance ramp.
- Upstream free flow station of a primary zone acts as the upstream free flow station for all nested zones belonging to that primary zone as shown in Figure 4.1.
- The downstream bottleneck station varies within the primary zone as shown in Figure 4.1.
- Capacity of the bottleneck station of each nested-zone is a predetermined value.
- Nested zone capacity, defined as the number of vehicles in a nested zone when it is "full" with vehicles, can be calculated as done for the primary zone.
- Each meter will have same six rates.
- Each Nested-zone follows the traditional Zone-based volume control
  \[ A + F + M = X + B + S \]
- Volume data is measured every 30 seconds.
- Metering rates are computed every 30 seconds using the past 5 minute volumes.
- Each meter can have multiple rate levels depending on the number of nested-zones in which it is present. For example Meter M1 in Figure 4.1 can have up to five rate levels. The most restrictive rate level is implemented.

It is worth to note that, even though nested zone concept is effective for local forward congestion, it has certain drawbacks. Nested zone control is not different from Minnesota algorithm in case of backward congestion. This algorithm, which is also the case with Minnesota zone algorithm, is highly dependent on bottleneck capacity. Determining a reliable bottleneck capacity for all the nested zones could be an issue.

IV. 2.2 Development of Nested Zone Simulation Module

Some of the important elements of Nested Zone data structure are shown in figure 4.2. Nested Zone data Structure has pointers to all the stations that are present in that zone. It has pointers to Starting Station (Start_Station), Ending Station (End_Station) and Number of stations in a zone. This way memory can be allocated dynamically to all the stations that are present in a zone. The data structure also has pointers to volume thresholds (Q_Rate), Zone capacity and
capacity of bottleneck station (Bottleneck_Cap). Zone capacity can be defined as the number of vehicles a zone can accommodate at its capacity.

The data structure has variables which store the values of all the important inputs like upstream mainline input demand (A), input demand from freeway to freeway ramp (F), Zone available space (S), unmetered onramp entrance demand (U), metered onramp volume (M), exit ramp volume (X) etc. These are important for the calculation of metering rate. Data structure stores the time when metering rate has to be computed. The final calculated metering rate level is written to the variable Curr_Rate_Level. The interaction between nested zone control module and simulation module is shown in Figure 4.3. Data related to Nested Zone control like Volume thresholds, Zone Capacity, Bottleneck Capacity etc. are read in Simulation Module. The sequence of steps involved in the reading of Nested Zone data is shown in Figure 4.4.

- First step calculates the number of valid nested zones that can be formed in all the primary zones of the freeway.
- Next we allocate memory to these Nested zones and assign the addresses to a Nested zone list defined in the Freeway Data structure.
- Once the memory is allocated successfully we read the data belonging to each nested zone.
- Once the Nested zone list is ready we assign them to meters i.e. each meter has pointers to all the Nested Zones in which it is present.

Compute_Station_values module reads detector data like volume, occupancy etc., from simulation module, for every second and creates packets of data aggregated over the data aggregation interval. Data from detectors belonging to the same mainline station are added to create station values.

Once the station values are calculated, the metering module calculates the metering rate using nested zone control module only when the simulation time is equal to metering computation time. Figure 4.5 shows the sequence of steps involved in the nested zone control module. In the control module, first we calculate the rate level for every nested zone using volume-based zone control method. Once the nested zone wide rate level is calculated, each meter selects the most restrictive rate level from all the overlapping nested zones in which it is included. After this, depending on users request, occupancy control module calculates metering rate using the occupancy control approach as described in the previous chapter. Each meter applies the most restrictive rate out of the nested-zone volume control and occupancy control.
Figure 4.2 Data Structure of Nested Zone
Figure 4.3 Interaction of Simulation module with other control modules
Figure 4.4 Nested Zone Read Data Module
Figure 4.5 Nested Zone Control Module
IV.3 Ramp Queue Management

IV.3.1 Overview of Queue management strategies

In this section two new approaches to manage long queues on entrance ramps are presented. For both the approaches it is assumed that each entrance ramp has queue detectors.

Single Threshold Approach

Each ramp is assumed to have a loop detector that can measure occupancy at the upstream of an entrance ramp. The occupancy data collected from queue detectors is used as input queue occupancy. The following steps are involved in algorithm

- Each ramp is assigned a predetermined occupancy threshold depending on the position of loop detector and length of the ramp.
- At every 30 seconds, queue occupancy averaged over the past 5 minutes is used as input queue occupancy.
- For every ramp, compare the input queue occupancy with queue threshold. If for a ramp queue occupancy is greater than queue threshold then increase the metering rate of that ramp by one level.
- Continue this procedure for every computation period untill the input occupancy falls back below the queue threshold.

This is a reactive type of algorithm, because it acts only when the occupancy exceeds the threshold. At the same time this approach does not opt for drastic changes in the metering rate. The changes are made in levels of one. This gives time for the freeway-ramp system to adjust to the changing metering rate. However this approach cannot be used for discharging queues aggressively.

Multiple threshold Approach

Similar to single threshold approach, occupancy data from queue detector is used to calculate the metering rate. The following steps are involved in this method

- Every Meter is assigned a set of five thresholds and six red times. These red-times are the same as currently used by the Minnesota Algorithm.
- After every computation period (30 sec), previous 5-minute average occupancy from queue detector is calculated.
- This occupancy is compared with the thresholds. A rate level is decided depending on in which region, defined by the five thresholds, this occupancy falls. See Table 4.1
- Rate level decided by queue is compared with the most restrictive rate level from occupancy control and volume control.
- If queue rate level is less than the most restrictive rate level then queue rate level is applied else the rate level decided by occupancy control or volume control is applied.

Table 4.1 Multiple Queue Thresholds

<table>
<thead>
<tr>
<th>Queue Threshold</th>
<th>Region</th>
<th>Rate Level</th>
<th>Red Time</th>
</tr>
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<td>6</td>
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<td>16.5</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;35 &amp; &lt;=45</td>
<td>4</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;45 &amp; &lt;=55</td>
<td>3</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td></td>
<td></td>
<td></td>
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<td>2</td>
<td>6.7</td>
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<td>65</td>
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<td></td>
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<tr>
<td>&gt;65</td>
<td>1</td>
<td>4.4</td>
<td></td>
</tr>
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</table>

Unlike single threshold approach, this approach can determine a metering rate directly depending on the value of input queue occupancy. Therefore this approach can lead to drastic changes in the metering rate. As a result, the freeway-ramp system may experience shocks. Another drawback is it has lots of thresholds to be determined. Queue rates may not be employed all the time during metering period but are calculated at every computation period and are compared with those of volume control and Occupancy control, which is not the case with Single threshold approach. The advantage of this approach is that ramp queues can be discharged faster than the single threshold approach.
IV.3.2 Development of Queue Management Simulation Module

For the implementation of the Queue Management procedures the existing Minnesota ramp meter data structure has been updated with few data storage and processing elements. Figure 4.4 shows the interaction of Queue Control modules with various other modules. The data reading part for Queue Control modules is done in the main simulation module and is done only when the user requests for a specific method of Queue control. The queue control modules use the aggregated queue station values calculated by Compute_Station_Values module.

Single Threshold Method

This approach, described in section 4.3.1, increases the metering rate by one level when the input queue occupancy is greater than the occupancy threshold. To accommodate this approach into the simulation, the MnDOT Ramp Meter data structure has been updated with a variable to store the Occupancy threshold, pointer to station from which Queue Occupancy is read and a Boolean variable INCREASE_METERING_RATE which becomes true if the queue occupancy exceeds the queue threshold.

The Queue_Control_A module, which controls queue using Single threshold approach, interacts with other modules only when requested by the user. This module acts only during the metering period. For every meter on the freeway, this module compares the queue occupancy with the occupancy threshold, and assigns appropriate value to the Boolean variable, which is then read by the metering module to increase the metering rate if true. The flow chart for the single threshold queue control metering is given in figure 4.6

Multiple Threshold Method

This approach actually selects the metering rates based on the region where the queue occupancy falls in the array of Queue threshold. Data elements necessary for this approach are pointer to the Queue station, array of volume threshold and the calculated metering rate level. The Queue_Control_B Module selects the metering rate level by comparing queue occupancy with queue thresholds and passes this rate to metering control module which uses this rate level only if the queue rate level is less than the most restrictive rate level decided by the Metering module. The flow chart for the multiple threshold queue control metering is given in figure 4.7
From metering control module

If Queue Occupancy < Queue threshold

- NO: Rate level = Rate level - 1
- YES: Rate level = Rate level

To Simulation module

Figure 4.6 Single threshold Queue control module flow chart (Queue_Control_A)

From metering control module

Find queue rate level by comparing queue occupancy with occupancy rate table

- NO
- YES: If Queue rate level < metering rate level

- NO: Rate level = Queue rate
- YES: Rate level = metering rate

To Simulation module

Figure 4.7 Multi threshold Queue control module flow chart (Queue_Control_B)
IV. 4 Performance Evaluation of Nested-Zone Metering Control

The proposed nested zone control has been tested on Freeway 169 using the macroscopic simulation model KRONOS. The following metering control types have been simulated to identify the performance trends of nested zone concept.

1. Zone and Occupancy Control (ZO): This is the current Minnesota metering control algorithm, which is a combination of zone control and occupancy control. Occupancy thresholds used in this case are 13%, 14%, 15%, 20% and 37%. The most restrictive rate of zone control and occupancy control is implemented.

2. Pure Zone Control (PZ): This is the case where only zone-based volume control was applied to the test site. The same set of volume thresholds used by the current Minnesota algorithm has been used in this case.

3. Pure Occupancy Control (PO): In this case only occupancy control was applied to the test site. The occupancy thresholds used were 13%, 14%, 15%, 20% and 37%.

4. Pure Nested Zone Control (PNZ): In this case the current zones of the test site were divided into valid nested zones and nested zone control was applied. The volume thresholds for each nested zone were calculated using the same procedure followed by the Minnesota algorithm.

5. Nested Zone Control and Occupancy Control (NZO): This is the case where both nested zone control and occupancy control was applied to the test site. The same set of volume thresholds calculated for the previous case has been used. The occupancy thresholds used were 13%, 14%, 15%, 20% and 37%. The most restrictive rate of the two controls was implemented.

These 5 cases were simulated for the test site using the same set of demand data and same set of 6 rate levels for two days. This analysis is divided into complete period and metering period (2:30 – 7:30).

Performance of whole simulation period

The density contour plots for day 1 and day 2 are shown in figures 4.8 – 4.11. It can be seen from these figures that PZ control resulted in most restrictive metering when compared to other four cases. Moreover, the contour plot for PZ control indicates that the simultaneous release of stored vehicles from all the metered ramps at the end of metering period creates local congestion at the bottleneck area in the middle of the test site. Further it is interesting to note that NZ and PO showed more distributed traffic pattern than other 3 cases for both the days. Comparing the density contour plots for ZO, PZ and PO it can be seen that due to the restrictive
Figure 4.8: Density contour plots of NZO and NZ control cases (Day 1).
Figure 4.9: Density contour plots of PO, PZ and ZO control cases (day 1).
Figure 4.10: Density contour plots of NZO and NZ control cases (day 2).
Figure 4.11: Density contour plots of PO, PZ and ZO control cases (day 2).
nature of zone control, the current Minnesota algorithm (ZO) also resulted in restrictive metering rates. This is because ZO is a combination of zone control and occupancy control (PZ and PO) and the most restrictive rate of the two (zone control and occupancy control) is selected. For both the days NZO case showed some congestion after the metering period, due to the implementation of restrictive rate selected from nested zone control and occupancy control. But this congestion is not as much as that created in PZ and ZO. Overall it can be said that PO and PNZ resulted in more distributed traffic. One reason for the similarity in PNZ and PO is that occupancy control (PO) determines metering rate for a ramp using the highest occupancy measurement detected from a set of pre-assigned downstream stations. By doing so PO control, similar to PNZ, can also capture the local congestion that can not be captured by Zone control.

The simulation results for the selected 5 cases are compared in Figure 4.12 and 4.13. These results are for the complete period. The tabulated results are shown in table 4.2 and 4.3. Figures 4.12 and 4.13 show that the case PNZ produced the maximum number of mainline vehicle miles with minimum number of ramp vehicle hours when compared to other 4 cases. This supports the argument about the less restrictive nature of PNZ control. Further this argument is supported by the high mainline vehicle hours produced by PNZ in both cases. It is also important to note that ZO (current Minnesota algorithm) produced the least amount of mainline vehicle miles for both days with low mainline vehicle hours and high ramp vehicle hours. This means that ZO control stored more vehicles on the ramp compared to other 4 cases by generating restrictive rates. The three cases PZ, PO and NZO showed different trends for both the days. One reason is that day2 experienced a high concentrated demand patterns during the peak period. Overall it can be said that PNZ distributed the demand during the peak period well compared to other four cases while ZO produced very restrictive metering rates and hence stored vehicles on the ramp during the metering period. These stored vehicles were released after the metering period creating high congestion.

**Performance during metering period**

The objective of dividing the results into metering period and after metering period is to study the nature of metering rates produced by different controls. The results are shown in figure 4.14 - 4.17. These figures show that during the metering period control case, PNZ produced the maximum number of vehicle miles with highest mainline vehicle hours, comparable mainline congested vehicle hours and lowest ramp vehicle hours. Control cases ZO and PZ, during the metering period, produced the least number of mainline vehicle miles with high ramp vehicle
Figure 4.12: Performance comparison of proposed metering algorithm (Day 1)

Figure 4.13: Performance comparison of proposed metering algorithm (Day 2)
Figure 4.14: Performance comparison of proposed metering algorithm during metering period (Day 1)

Figure 4.15: Performance comparison of proposed metering algorithm after metering period (Day 1)
Figure 4.16: Performance comparison of proposed metering algorithm during metering period (Day 2)

Figure 4.17: Performance comparison of proposed metering algorithm after metering period (Day 1)
hours, low mainline vehicle hours and low mainline congested vehicle hours compared to other three cases. Further the results for “after metering period (when there is no ramp metering)” show that PNZ produced the least number of mainline vehicle miles with least mainline vehicle hours, least mainline congested vehicle hours and least ramp vehicle hours. On the other hand ZO and PZ control cases produced the maximum mainline vehicle miles with high mainline congested vehicle hours, high mainline vehicle hours and also high ramp vehicle hours compared to other three cases. These observations suggest that during the metering period ZO and PZ produced restrictive rates and stored vehicles on the ramps while PNZ was less restrictive and had comparatively less number of vehicle stored on the ramp. Hence, in the case of ZO and PZ, after the meters were shutdown all the stored vehicles were released onto the freeway creating congestion. This congestion further blocked vehicles from entering the freeway and hence resulted very in high ramp vehicle hours compared to other cases.

Figures 4.18 – 4.19 give the 5-minute average ramp vehicle-hours for the metering period at each entrance ramp resulted from the control cases selected. Figure 4.18 and 4.19 suggest that during the peak-congested period, Pure Zone Control (PZ) resulted in high ramp vehicle hours with an exception in zone 3D. Second to PZ was Zone and Occupancy Control (ZO) suggesting that zone-based volume control resulted in more restrictive rates when compared to other three cases. Pure Occupancy control (PO) produced the least amount of average ramp vehicle hours in Zones 3B and 3C while Pure Nested-zone control (PNZ) resulted in least amount of vehicle hours in zones 3A and 3D. Using figure 4.19 it can be said that during the peak-congested period PNZ resulted in more mainline vehicle miles and can be said as a good control option. Figures 4.20 and 4.21 for the less-congested period show similar trends as shown by figures 4.18 and 4.19 supporting that PNZ is a better control option than the other four. Similar results were found for Day2.
Figure 4.18 Ramp 5-minute Average Vehicle hours for peak congested period (Day1)

Figure 4.19 Total mainline vehicle-miles during peak-congested period (day1)
Figure 4.20 Ramp 5-minute Average Vehicle hours for less-congested period (Day 1)

Figure 4.21 Total mainline vehicle-miles during less-congested period (day1)
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<th>Ramp Hrs</th>
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Table 4.2 Day1 system performance for complete duration

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<td>ZO</td>
<td>4626</td>
<td>1469</td>
<td>6095</td>
<td>7.24</td>
<td>289242</td>
<td></td>
</tr>
<tr>
<td>PZ</td>
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<tr>
<td>PO</td>
<td>4818</td>
<td>1331</td>
<td>6149</td>
<td>42.08</td>
<td>294369</td>
<td></td>
</tr>
<tr>
<td>PNZ</td>
<td>4881</td>
<td>1294</td>
<td>6175</td>
<td>35.95</td>
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</tr>
<tr>
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<td>6180</td>
<td>19.41</td>
<td>294582</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Day1 system performance during Metering period

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Main Hrs</th>
<th>Veh. Hrs</th>
<th>Ramp Hrs</th>
<th>Veh. Total Hrs</th>
<th>Veh. Cong. Veh. Hrs</th>
<th>Main Veh. Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>5089</td>
<td>1614</td>
<td>6703</td>
<td>126.12</td>
<td>303494</td>
<td></td>
</tr>
<tr>
<td>PZ</td>
<td>5381</td>
<td>1548</td>
<td>6929</td>
<td>323.43</td>
<td>305739</td>
<td></td>
</tr>
<tr>
<td>PO</td>
<td>5128</td>
<td>1532</td>
<td>6660</td>
<td>136.63</td>
<td>303717</td>
<td></td>
</tr>
<tr>
<td>PNZ</td>
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<td>1400</td>
<td>6898</td>
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<td></td>
</tr>
<tr>
<td>NZO</td>
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</tr>
</tbody>
</table>

Table 4.4 Day2 system performance for complete duration

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Main Hrs</th>
<th>Veh. Hrs</th>
<th>Ramp Hrs</th>
<th>Veh. Total Hrs</th>
<th>Veh. Cong. Veh. Hrs</th>
<th>Main Veh. Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>4654</td>
<td>1565</td>
<td>6219</td>
<td>65.12</td>
<td>281281</td>
<td></td>
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<tr>
<td>PZ</td>
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<td>1496</td>
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<td>330.32</td>
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</tr>
<tr>
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<td>6268</td>
<td>82.13</td>
<td>283454</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 Day2 system performance during Metering period
IV. 5 Evaluation of Queue Management Strategies

In this simulation analysis, the proposed queue control methods were evaluated by simulating them with proposed nested zone control (PNZ) and current Minnesota control algorithm (ZO). The same data set and metering rates have been used. To identify trends and sensitivity of proposed queue control methods, the queue occupancy thresholds for each control have been varied.

IV.5.1 Evaluation of Single Threshold Method.

To identify the trends and sensitivity of single threshold approach, the queue occupancy threshold was varied as shown id table 4.6. The analysis was done for control case ZO and PNZ separately. It is important to note that a high queue occupancy threshold results in less aggressive queue control.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Queue Occupancy Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>QA1</td>
<td>15</td>
</tr>
<tr>
<td>QA2</td>
<td>30</td>
</tr>
<tr>
<td>QA3</td>
<td>45</td>
</tr>
<tr>
<td>QA4</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 4.6 Variations in queue occupancy threshold (single threshold method)

Analysis with Current Minnesota algorithm (ZO Control case)

The results with varying queue threshold for ZO control case are shown in figure 4.22 and 4.23. These figures show that for both the days the ZOQA4 case resulted in highest mainline vehicle miles with low mainline vehicle hours and similar mainline congested vehicle hours. As expected, for both the days as queue occupancy threshold increased the ramp vehicle hours decreased. For day 1, which experienced a less concentrated peak period demand, no queue control resulted in the highest mainline congested vehicle hours. This is because of the restrictive nature of ZO control, which stored vehicles in the ramp during metering period, released the stored vehicles after the metering period creating congestion on the mainline. But for day 2, due to its concentrated peak period demand, congestion was created both during the metering period and after metering was shutdown. This resulted in similar mainline congested vehicle hours. Moreover it can be noted that mainline vehicle hours for both the days increased and then decreased except for the peaks were different for both the days. Overall it can be said that case ZOQA4 performed well on day 1 and its performance was moderate on day 2.
Figure 4.22: Simulation results with different queue occupancy thresholds applied to ZO control case (day 1)
Figure 4.23: Simulation results with different queue occupancy thresholds applied to ZO control case (day 2)
Figure 4.24: Simulation results with different queue occupancy threshold applied to NZ control case (day 1)
Figure 4.25: Simulation results with different queue occupancy threshold applied to NZ control case (day 2)
**Analysis with Nested Zone Control case (PNZ)**

The results with varying queue threshold for PNZ control case are shown in figure 4.24 and 4.25. These figures show that for both the days, no queue control case resulted in maximum mainline vehicle miles with low mainline vehicle hours and low mainline congested vehicle hours. As expected, for both the days as queue occupancy threshold increased the ramp vehicle hours increased and mainline vehicle hours decreased. Further for day 1, which experienced a less concentrated peak period demand, mainline vehicle miles increased with increase in queue occupancy threshold as expected. However for day 2 the trend was different because of its concentrated peak period demand pattern. Overall it can be said that no queue control case with PNZ control resulted in better performance compared to other cases.

**IV.5.2 Evaluation of Multiple Threshold Method.**

To identify the trends and sensitivity of multiple threshold approach, the queue occupancy thresholds were varied as shown in table 4.7. The analysis was done for both ZO and PNZ control cases. It is important to note that a higher set of queue occupancy thresholds means less aggressive queue control.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Queue Occupancy Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB1</td>
<td>15%-20%-25%-30%-35%</td>
</tr>
<tr>
<td>QB2</td>
<td>25%-30%-35%-40%-45%</td>
</tr>
<tr>
<td>QB3</td>
<td>30%-40%-50%-60%-70%</td>
</tr>
</tbody>
</table>

Table 4.7 Variations in queue occupancy thresholds set (Multiple threshold method)

**Analysis with Current Minnesota algorithm (ZO Control case)**

The results for varying set of queue thresholds simulated with current Minnesota algorithm are shown in figures 4.26 and 4.27. These figures show that, as expected, with the increase in queue occupancy thresholds the ramp vehicle hours increased. Moreover, the mainline vehicle hours decreased and mainline congested vehicle hours decreased for both days. The decrease in mainline vehicle hours was continuous for day 1 while day 2 showed similar mainline vehicle hours for the queue control cases and a decreased mainline vehicle hours for no control case. Further, it is worth noting that the difference in mainline congested vehicle hours between queue control cases and no queue control case is very high. This is because the aggressive nature of the multiple threshold queue control, which can implement very high rates,
Figure 4.26: Simulation results with different queue occupancy threshold sets applied to ZO control case (day 1)

Figure 4.27: Simulation results with different queue occupancy threshold sets applied to ZO control case (day 2)
creates congestion on the mainline. It can also be seen that for day 1 the mainline vehicle miles decreased with increase in queue thresholds but for day 2 the mainline vehicle miles increased. The restrictive nature of Minnesota control algorithm and aggressive nature of multiple threshold queue control can result in high fluctuations to metering rates. Added to these high fluctuations in metering rates, a concentrated peak period demand like demand for day 2, a more aggressive queue control (lower values of queue thresholds like ZOQB1) will result in high levels of congestion on the mainline and there by decreases the mainline vehicle miles. Overall it can be said that Minnesota algorithm with no queue control case resulted in better performance compared to queue control cases.

**Analysis with Nested Zone algorithm (PNZ Control case)**

The results for varying set of queue thresholds simulated with nested zone algorithm are shown in figures 4.28 and 4.29. These figures show that, as expected, with the increase in queue occupancy thresholds the ramp vehicle hours increase. Moreover, the mainline vehicle hours and mainline congested vehicle hours decreased for both days, but the decrease in mainline vehicle hours was continuous for day 1 while day 2 showed similar mainline vehicle hours for the queue control cases and a decreased mainline vehicle hours for no queue control case. Though these results are consistent with Minnesota algorithm cases, the less restrictive nature of nested zone algorithm lead to increased mainline vehicle miles for both the days, which was not the case with Minnesota algorithm. Overall in this case too the no queue control performed better than queue control cases.

**Comparison of Nested-zone control and other metering methods**

The results of nested zone control (PNZ) compared with fuzzy and Denver metering methods are shown in figures 4.30 and 4.31. These figures show that on both the days nested zone control resulted in the least number of mainline congested vehicle hours and fuzzy control resulted in the maximum number of ramp vehicle hours. On day 1 PNZ control resulted in the maximum number of mainline vehicle miles while on day 2 fuzzy resulted in maximum number of mainline vehicle miles. However on day 2 fuzzy also resulted in maximum mainline vehicle hours, maximum mainline congested vehicle hours and maximum ramp vehicle hours. This is because on day 2 fuzzy control resulted in higher congestion compared to PNZ on mainline and there by decreased the number of vehicles entering the mainline from ramps. This resulted in higher vehicle hours both on mainline and ramp.
Figure 4.28: Simulation results with different queue occupancy threshold sets applied to NZ control case (day 1)

Figure 4.29: Simulation results with different queue occupancy threshold sets applied to NZ control case (day 2)
IV.3 Adaptive Metering with Fuzzy Coordination

IV.3.1 Overview of adaptive metering approach

The new adaptive metering strategy developed in this study adopts the zone-based control structure used in the current Minnesota metering system, which divides a given freeway into multiple zones whose downstream boundaries are known bottlenecks. The new control method treats a zone as the control unit and determines the zone-wide rate level, which is applied to all the ramps within a zone to calculate final metering rates. Each ramp in a zone is assigned minimum and maximum rates as in the most existing metering systems.

Figure 4.30 shows the framework of the new adaptive algorithm, which starts with estimating zone-wide congestion indices using the measured detector data from the mainline detectors in each zone. The zone coordination module, which adopts a fuzzy-logic based approach, then determines the degree of coordination between two successive zones using the congestion indices of two zones as well as the ramp queue condition of current zone. The coordination factor is given to the zone-wide adaptive control module, which calculates a new zone-wide rate level by reflecting the current traffic condition in a given zone and the conditions on the downstream section quantified by the coordination factor. The zone control module adjusts the current zone-wide rate level by determining the rate-level adjustment factor, $\alpha_i^t$, using an adaptive control rule that changes through time reflecting the current rate level. The new zone-wide rate level is then determined as follows:

$$R_{L,i}^{t+1} = R_{L,i}^t * \alpha_i^t$$

where, $R_{L,i}^t$ = rate level for zone i at time t,

$\alpha_i^t$ = rate level adjustment factor for zone i at time t.

Formulation of zone-wide congestion index

The new metering method is based on the newly defined zone-wide congestion index, which quantifies the zone-wide traffic level using all the available point measurements within each zone. In this research, two types of zone-wide congestion index are formulated depending on the types of available data in real time. The first index quantifies the congestion level using only volume and occupancy data, while the second one uses the estimates of density at each detector station assuming volume and speed data are available.
Figure 4.30. Framework of the Adaptive Metering Strategy with Fuzzy coordination
\* V/O-based index: \( C_i^t \)

\[
C_i^t = \sum w_{ij} (V_{ij}^t + O_{ij}^t)/(V_{ij}^t + O_{ij \text{ max}})
\]

\* Density-based index:

\[
K_i^t = \sum w_{i,j} k_{ij}^t
\]

where,

\( C_i^t = \) volume/occupancy based congestion index for zone i during time interval t,

\( V_{ij}^t = \) measured volume at detector station j in zone i during time interval t,

\( O_{ij}^t = \) measured occupancy (%) at detector station j in zone i during time interval t,

\( O_{ij \text{ max}} = \) maximum occupancy (%) at detector station j in zone i,

\( K_i^t = \) density-based congestion index for zone i for time interval t,

\( w_{i,j} = \) weight for detector station j in zone i, \( (\sum w_{i,j} = 1.0) \)

\( k_{ij}^t = \) estimated density at detector station j in zone i for time interval t.

In the above formulation, the volume/occupancy based index quantifies the zone wide traffic level on a 0 to 1 scale, while the density based index represents the zone-wide weighted average density.

**Zone-wide adaptive metering module**

At each time interval, the zone-wide adaptive metering module determines \( \alpha_i \), i.e., the rate-level adjustment factor for each zone, which has minimum and maximum rate levels predetermined, i.e.,

\[
R_{L, \text{min}} \leq R_{L}^{t+1} = R_{L}^t \cdot \alpha_i^t \leq R_{L, \text{max}}
\]

Therefore, the range of \( \alpha_i^t \) with the current rate level \( R_L^t \) is also limited as follows;

\[
R_{L, \text{min}}/R_{L}^t \leq \alpha_i^t \leq R_{L, \text{max}}/R_{L}^t
\]

Figure 2 illustrates the adaptive control rule with the volume/occupancy based congestion index. \( C_{d,i}^t \) denotes the desired congestion index level for zone i at time t and is determined as follows;

\[
C_{d,i}^t = C_{d,i} \cdot \beta_{i}^t
\]

Where \( C_{d,i} = \) desired congestion index level for zone i under normal condition (constant),

\( \beta_{i}^t = \) coordination factor, determined by the coordination module, for zone i for time interval t.
At each control interval, the adaptive control rule in Figure 4.31 determines the new range of $\alpha_i^t$ corresponding to the current rate level and tries to find new $\alpha_i$ value that can reduce the difference between the desired and current congestion level during the next time interval for a given zone, i.e.,

- $\alpha_i^t > 1.0$ if $C_{d,i}^t - C_i^t > 0$
- $\alpha_i^t = 1.0$ if $C_{d,i}^t - C_i^t = 0$
- $\alpha_i^t < 1.0$ if $C_{d,i}^t - C_i^t < 0$

Further, by making the desired congestion index level as the time-variant variable, the control rule can continuously adapt to the current traffic environment for a given zone. Figure 4.32 shows the same adaptive rule with the density-based congestion index, $K_i^t$. In this figure, $K_{d,i}^t$ represents the desired zone-wide density level for the zone $i$ during time interval $t$, and $k_{jam}$ is the jam density.

**Fuzzy coordination module**

The coordination module determines the desired congestion index or density level for a given zone using a fuzzy logic. Specifically, it determines the value of the coordination factor, $\beta_i^t$, for each zone by considering the traffic conditions at current and downstream zones as well as the ramp queue conditions of the current zone. For example, when the congestion level of the downstream zone is ‘very big’ then it tries to adjust the rate level of upstream zone ‘very small’. The input to the fuzzy coordination module for a zone $i$ includes the current zone-wide congestion levels for both zone $i$ and zone $i+1$, i.e., downstream zone of $i$, and the queue congestion level for the zone $i$. The fuzzy classes and the membership functions used for fuzzification of the measurements are illustrated in Figure 4.44. Further Table 4.8 includes the fuzzy rules that link the fuzzified measurements to the determination of the coordination factor, $\beta_i$. Figure 4.44 also includes the fuzzy classes and membership functions for $\beta$ whose range is a user-specified input. The final defuzzification to calculate $\beta$ is done by finding the centroid of the combined rule outcome (7). The weights of fuzzy rules in this coordination module can be changed in real time by traffic operators to respond to certain situations as they arise.
Figure 4.31. Adaptive control rule with v/o-based congestion index

Figure 4.32. Adaptive control rule with zone-wide weighted density
Metering rate calculation

Finally, the metering rates for each individual meter can be calculated with the given minimum and maximum rates for each meter and with the newly calculated zone-wide rate level, i.e.,

$$R_{j,t+1} = R_{j,\text{min}} + (R_{j,\text{max}} - R_{j,\text{min}}) \times (R_{t,\text{max}} - R_{t,\text{min}}) / (R_{t,\text{max}} - R_{t,\text{min}})$$

where, $R_{j,t}$ = metering rate for ramp $j$ in zone $i$ during time interval $t$,

- $R_{j,\text{min}} =$ minimum metering rate for ramp $j$,
- $R_{j,\text{max}} =$ maximum metering rate for ramp $j$,
- $R_{t,\text{max}} =$ maximum rate level
- $R_{t,\text{min}} =$ minimum rate level

Performance evaluation of the new adaptive metering strategy

The performance of the new metering strategy was evaluated using simulation and its performance was compared with that of the current Minnesota algorithm. For this evaluation, the same 16-mile section of the northbound 169 freeway in Minneapolis, Minnesota, was used and the adaptive metering algorithm was coded into the Kronos macroscopic simulation model.

The sample freeway section that has been controlled by the Minnesota metering system, which divides the sample freeway into four metering zones. All the ramp meters in each zone have 6 rates pre-allocated by the system based on historical demand pattern at each ramp. The current zone-control algorithm of the Minnesota system selects one rate level every 30 seconds for each zone using the volume measurements from the upstream boundary and ramps within a zone with pre-defined volume thresholds, which are derived with the assumed capacity values at the downstream boundary, i.e., bottleneck, of each zone. Each entrance ramp is also assigned up to 9 downstream detector stations and the maximum occupancy from those stations is used to select the occupancy rate level for the given ramp. The volume-based and occupancy-based rates are then compared and the more restricted rate is implemented for the next control interval.
Figure 4.33. Fuzzy classes used in the coordination module
Table 4.8. Fuzzy rules for Coordination module

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight</th>
<th>Premise</th>
<th>β Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>ZONE_K_VB or ZONE_C_VB</td>
<td>VS</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>ZONE_K_B or ZONE_C_B</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>ZONE_K_M or ZONE_C_M</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>ZONE_K_S or ZONE_C_S</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>ZONE_K_VS or ZONE_C_VS</td>
<td>VB</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>NEXT_ZONE_K_VB or NEXT_ZONE_C_VB</td>
<td>VS</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>NEXT_ZONE_K_B or NEXT_ZONE_C_B</td>
<td>S</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>NEXT_ZONE_K_M or NEXT_ZONE_C_M</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>NEXT_ZONE_K_S or NEXT_ZONE_C_S</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>NEXT_ZONE_K_VS or NEXT_ZONE_C_VS</td>
<td>VB</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>QUEUE_K_VB or QUEUE_C_VB</td>
<td>VB</td>
</tr>
</tbody>
</table>

*VB = Very Big, B = Big, M = Medium, S = Small, VS = Very Small
In this analysis, the new metering algorithm was simulated for the sample freeway using the same zone configuration of the current Minnesota algorithm. Further, the same minimum and maximum rates for each ramp used in the Minnesota algorithm were also used for the new metering simulation. A set of loop detector data collected from one weekday in October 2000 was used as the traffic demand for the sample freeway. The fuzzy classes and membership functions presented in Figure 4 and Table 1 were used for the coordination module. Finally, the following parameters were used for both coordination and zone control module:

\[ R_{L, \text{min}} = 1.0, \quad R_{L, \text{max}} = 6.0, \quad \beta_{\text{min}} = 0.7, \quad \beta_{\text{max}} = 1.3 \]

Figure 4.45 shows the performance sensitivity of the new adaptive algorithm with respect to the variations in the system-wide, volume/occupancy-based desired congestion index. It can be noted that as the value of the target congestion index increases, more vehicles enter the main freeway resulting in the increased mainline vehicle-hours. It can also be noted that there exists an optimum target index, which minimizes mainline congestion while maximizing mainline vehicle-miles. Figure 4.46 shows the performance sensitivity with respect to the density-based, target congestion index. In case of the density-based target index, smaller index resulted in more restrictive control producing less mainline congestion but higher ramp vehicle-hours. It should be noted that the target congestion index can be adjusted in real time to reflect time-variant traffic conditions. Figure 4.47 compares the performance of the new adaptive metering with that of the current Minnesota algorithm for the sample freeway. Since the current Minnesota algorithm does not use any ramp-queue override policy, the fuzzy coordination module in the adaptive metering did not include the effects of ramp queue in determining the level of coordination between two zones for this evaluation. As indicated, the new adaptive approach outperformed the current Minnesota algorithm in terms of mainline vehicle-miles and congested vehicle-hours, i.e., more vehicle-miles with less amount of congestion. It needs to be noted that the Minnesota algorithm has been optimized for the sample freeway section and the new adaptive metering does not require link capacity.
Figure 4.45. Performance sensitivity of adaptive metering with respect to system-wide desired congestion index (volume/occupancy based)

Figure 4.46. Performance sensitivity of adaptive metering with respect to system-wide desired congestion index (density based)
Figure 4.47. Performance comparison between adaptive and current Minnesota metering algorithms
V. DEVELOPMENT AND EVALUATION OF ON-LINE BOTTLENECK CAPACITY ESTIMATION PROCEDURES

V.1 Introduction

Performing effective management of freeway networks requires continuous assessment of traffic conditions and frequent adjustment of operational parameters, so that the most effective strategy can be implemented for a given situation. The most critical parameter for conventional ramp metering schemes is the capacities of bottlenecks whose locations can vary depending on surrounding traffic and weather conditions. In this research, two alternative approaches are developed to estimate in real time the time-variant capacity values for a fixed bottleneck location. They are 1) the adaptive approach with Kalman Filter, and 2) Neural-network based estimation method. The rest of this chapter describes each approach with preliminary testing results.

V.2 Adaptive Estimation Approach with Kalman Filter

Freeway bottlenecks are, in general, caused by physical geometry changes, e.g., lane-drop, and/or by the reduction of capacity caused by the conflict resulting from the interrupted flow such as merging or weaving. While the capacities of conflict-based bottlenecks are heavily dependent upon the time-variant traffic patterns, the bottlenecks due to geometry changes can also be wiped out by a downstream queue that grows past the bottleneck. In addition, the capacities of both type bottlenecks are further affected by weather and pavement conditions.

In this section, an adaptive method to estimate the capacity of a bottleneck is developed. Based on the statistical analysis with historical volume-occupancy data, it is assumed that the critical occupancy value, $O_{cr}$, i.e., the occupancy corresponding to the observed maximum volume, remains constant for a given location. Further, the volume-occupancy relationship was modeled with a simple quadratic function as follows:

$$V_{\text{max}} = \gamma_k \left[ \alpha \cdot O_{cr}^2 + \beta \cdot O_{cr} \right] \quad \text{[-]} \quad [5.1]$$

Where, $V_{\text{max}} =$ Maximum possible volume estimated at time interval $k$,

$\gamma_k =$ Adjustment factor updated in real time,

$\alpha$ and $\beta =$ Coefficients calibrated with historical data.
The algorithm recursively determines $\gamma_k$ by comparing the estimated volume $V^*_k$ with the measured $V_k$, at each time step using the Kalman Filter (24), which treats $\gamma_k$ as the state variable following the random work process, i.e.,

$$V^*_k = \gamma_k [\alpha*O_k^2 + \beta*O_k] + v_k$$
$$\gamma_{k+1} = \gamma_k + w_k$$

where, $O_k = $ measured occupancy value at time interval $k$.

$\nu_k, w_k = $ white noise.

After the adjustment factor is determined with the data up to the time interval $k$, the algorithm predicts $V_{\text{max}}$ using the equation [5.1] and repeats the process continuously through time. In the above formulation, the Kalman Filter algorithm identifies the optimal unbiased estimates of the state variable, i.e., $\gamma_{k+1}$, by using the most recent prediction error. Further, the non-stationary random walk process has been successfully applied to model physical systems that are subject to rapid variation (25, 26).

Figure 5.1 shows the volume-occupancy relationship of one bottleneck location on the I-35W freeway in Minneapolis, Minnesota, on November 1, 1996, which was used as the historical data to predict the capacity values at the same location. Figure 5.2 shows the preliminary testing results at the same detector location on November 15, 1996, where there was snow in the morning period. The data from November 1 was used to calibrate the constant parameters in the predictor. As indicated in the figure, the algorithm shows the adaptability of the predictor with the prevailing weather and traffic conditions.
Figure 5.1. Volume-Occupancy relationship at Detector 897 on November 1, 1996

Figure 5.2. Capacity prediction module test results on November 15, 1996
V.3 Neural Network-based Estimation of Bottleneck Capacity

In this section, a neural network-based approach is developed to predict the volume of a detector station using the past volume measurements from upstream and downstream detector stations for a given location. The proposed approach is based on the assumption that the traffic state at a mainline location is continuously affected by the traffic conditions at the surrounding areas of a given location, i.e., both upstream and downstream. Further, due to the inherent randomness and highly non-linearity of the traffic behavior, the time-dependent evolution process of traffic flow state is difficult to model in real time with the conventional, fixed-model based approach. Figure 5.3 shows the detector stations for the sample freeway site used in this study. This site is located at the trunk highway 169 in Minneapolis and includes 3 mainline stations, 2 on-ramps and one off-ramp. The neural network proposed in this research predicts the volume at the mainline detectors, 1967 and 1968, for the next one-minute interval using the past ten one-minute volumes measured from all the upstream and downstream detectors including ramps. Figure 5.4 illustrates the structure of the proposed neural network with one hidden layer.

In this research, the proposed neural network was trained by using a back-propagation learning algorithm provided by the Neural Network Toolbox of the MATLAB software (27). In particular, the gradient descent method with the Levenberg-Marquardt optimization technique was used with the mean square error 0.35 as the performance index for stopping criteria. The maximum number of iterations was set to 50 and the training was completed after 10 epochs. The amount of training time needed for the convergence of the neural network depends on the number of neurons in the hidden layer. As the number of hidden layers and the number of hidden layer neurons increase, the memory requirement for computing and the time for the convergence of the performance function also increase. In this research, the number of neurons in the hidden layer was varied for different training runs and the number 40 was found to be appropriate as the network converged with reasonable computation time. Thus the final trained network has 70 input neurons, one hidden layer with 40 neurons and 2 output neurons. The convergence rate of the proposed neural network is shown in Figure 5.5.

The volume data used for training was collected from 3:00p.m. to 7:00p.m. on October 18, 2001. Figure Figures 5.6 and 5.7 show the one-minute volume prediction results at the two detector locations with the trained neural-network for October 25, 2001. The mean absolute error for two predictions is approximately 5.5 vehicles/min.
Figure 5.3 Example freeway site

Figure 5.4 Structure of the neural network for volume prediction

Output: predicted one-minute volumes at detectors 1968, 1967
Figure 5.5 Convergence rate of the proposed neural network

Figure 5.6 Prediction results at Detector 1967

Figure 5.7 Prediction results at Detector 1968
VI. CONCLUSIONS AND FURTHER RESEARCH NEEDS

Existing operational metering algorithms for traffic-responsive, coordinated control can be categorized into three groups: 1) the local-control based incremental group coordination approach being implemented in Denver, Colorado, 2) the bottleneck-based section-wide coordination approach adopted by California, Virginia and Minnesota, and 3) the fuzzy-logic based implicit coordination approach currently being implemented in Seattle, Washington. The bottleneck-based section-wide control approach represents the conventional concept of keeping 'expected' flow levels at pre-determined bottlenecks under their capacities by simultaneously determining the metering rates of all the entrance ramps in a section with given link capacity and expected demand. The other two approaches, i.e., incremental coordination and fuzzy metering, try to identify bottlenecks in real time and do not explicitly require the estimation of link capacity values or prediction of traffic demand. Further, in most operational metering algorithms, some form of ramp-queue management policies are built into their metering algorithms, while Minnesota and San Diego are the only systems that do not employ an explicit queue override policy.

This research conducted performance analysis of three algorithms representing each coordination approach, i.e., the Denver incremental coordination, the Seattle Fuzzy metering and the Minnesota explicit section-wide coordination approaches, using a macroscopic simulation model under the same geometry and traffic demand conditions. The simulation results from the incremental and fuzzy metering algorithms indicated potential negative impacts of ramp-queue override policies on the management of mainline congestion. In case of the incremental algorithm, the case without queue control produced better performance than the case with queue control, i.e., more mainline vehicle-miles with less congested vehicle-hours, while the Fuzzy metering without employing queue rules showed compatible vehicle-miles with less congestion than the other cases with queue weights. Further, the Minnesota algorithm, which does not employ queue override policies, consistently produced more evenly distributed traffic flows on mainline with lower level of congestion than other algorithms. However, the comparison of the average ramp vehicle-hours indicated that the Minnesota algorithm resulted in more number of ramps with high vehicle-hour values than other algorithms.
The performance analysis of the three algorithms indicates that, with proper calibration of system parameters, there still exits the advantage of explicit section-wide coordination method over the incremental or fuzzy-based, implicit coordination approach in terms of distributing traffic demand over space and time. However, considering the increased frustration level of drivers on ramp waiting time, the balanced management of ramp queue and mainline congestion becomes one of the major issues with the Minnesota algorithm, which has not adopted explicit ramp-queue management policies. Further, the simplicity of the incremental coordination approach and the flexibility of the fuzzy metering in adjusting system parameters in real time were also noted in this research.

Based on the above analysis, two new alternative metering approaches were developed and evaluated in this research. The nested-zone method is based on the conventional bottleneck-based zone structure and tries to capture local congestion within a primary zone by introducing sub-nested zones. While in this research only the forward nested-zone concept was implemented, a combined approach with both forward and backward nested zones needs to be tested in the subsequent research. The other method presented in this research employs adaptive metering method with fuzzy-based coordination. It is based on the conventional zone-based control structure, but treats a zone as a control unit and employs a fuzzy logic-based intra-zone coordination scheme. Further newly defined congestion index is used to quantify zone-wide congestion level, which makes the new algorithm less sensitive to the detector malfunction. Unlike existing zone-wide coordination methods, the new metering strategy does not require the estimation of link capacity or demand prediction, which has been major difficulty in real time operations. The preliminary test for both alternative strategies using simulation with an example freeway in Minnesota showed promising results in terms of reducing congestion and increasing throughput on the mainline.

Further research needs include the extension of the nested-zone metering approach by combining forward and backward zone concepts, so that both forward and backward shock waves can be detected as early as possible. The adaptive metering approach without using predetermined bottleneck capacities also needs further testing. Finally, comprehensive testing of the on-line capacity estimation procedures developed in this research needs to be conducted.
References

Appendix
Slides presented at the Metering Group Discussions at Traffic Management Center
Operational metering algorithms in U.S.

- Fixed time control: 16 out of 24 cities with metering
- Local Traffic-Responsive Control: Chicago, Toronto, San Diego

- Use pre-determined volume/occupancy thresholds
- Select one rate every 20 or 30 seconds from Rate Table

- Traffic-Responsive Coordinated Metering for Multiple Ramps: Denver, Seattle, California (LA), Virginia (D.C.), Minnesota

Denver Metering System (30 Meters)

Vol/Occ detection per 20 sec.
(Speed not used for metering)

Each meter has 6 rates

Starts with Local control using pre-determined Volume/Occupancy Thresholds

Increase Metering Rate when Queue is detected
: No spill-back to local street
Primary group coordination (upstream ramp rate restricted by one level)

Secondary group coordination (after all the ramps in primary group become critical)

California (System Wide Adaptive Ramp Metering: Being installed)
SWARM rate calculation procedure

Step 1) Required bottleneck density at the current time step
    \[ \text{Current density} - (\text{predicted density} - \text{saturation density}) / T \]

Step 2) Needed volume reduction at the detector station upstream of a meter
    \[ (\text{Local density} - \text{Required bottleneck density}) \times (\text{number of lanes}) \times \]
    \[ (\text{Distance to next downstream ramp}) \]

Step 3) Metering rate = current ramp volume + (Volume Reduction)

Virginia (Being operated at I-395 and I-66 in D.C. area: 26 meters)

- **RDL:** Maximum Permissible Link Volume
- **PRD:** Arrival Link Volume
- Metering rate for link n (1 min update)
  \[ \text{RDL}(n) - \text{PRD}(n) \]
- Queue Control: If Queue occupancy >= Threshold
  then Maximum Rate
Seattle, Washington (110 meters)

Every 20 seconds, use 1-minute data (Volume, Occupancy, Speed)
Detector spacing = 1/4 - 1/2 mile

Switched from 'Bottleneck algorithm' to 'Fuzzy metering' in 1999

Bottleneck algorithm

Issues: Detector Error => False 'Bottleneck section'
Frequent Manual Queue Override by Operators
Fuzzy Metering

Use natural linguistic variables and tries to mimic heuristics of Human Reasoning by employing multiple Rules simultaneously

\[ OC, SP \rightarrow \text{QO} \rightarrow \text{AQO} \rightarrow \text{DO (Max. occupancy)} \rightarrow \text{DS (Lowest speed)} \]

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight</th>
<th>Source Rate</th>
<th>Rate</th>
</tr>
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<td>VS</td>
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<tr>
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<td>1.0</td>
<td>OC_B</td>
<td>S</td>
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<td>-</td>
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</tr>
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<td>1.0</td>
<td>DO_VB</td>
<td>VS</td>
</tr>
<tr>
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<td>2.0</td>
<td>QQ_VB</td>
<td>VB</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td>AQO_VB</td>
<td>VB</td>
</tr>
</tbody>
</table>

Fuzzy Classes and Membership Functions

If 'Crisp' occupancy 15% => 0.2 for VS => Rate is VB to a degree of 0.2
0.6    S    Rate is B to a degree of 0.6
Fuzzy Metering (continued)

Detector station

$M_i =$ Metering rate for ramp $R_i$

Implicit Coordination of Multiple Ramps
High Weights on Queue Occupancy Data

Minneapolis

Detector
(Vol/Occ per 30 sec)

(1) Volume-based zone-wide control
At + Mt - Xt = Bi

(2) Occupancy-based individual control (Thresholds-based)

Every 30 sec. Compare (1) and (2), Select More Restrictive Rate

No Queue Override
Denver Ramp Metering System

Total 30 meters (4 major groups), Updated every 20 seconds

Detection System

Mainline: Double Loops (20ft apart) near each Ramp (Vol, Occ, Spd/20 s) Uses first loop for vol/occ.

*No mainline detector station between two ramps

Entrance Ramp: Single Loop (Vol, Occ/20 s), Queue and HOV detectors
Two lane simultaneous release (*No Exit Ramp Detector)

Metering uses 1min. smoothed Vol. and Occupancy Smoothing factor: 5 -> Mainline 3 -> Ramp
Metering Operations (General)

Automatic Turn On/Off
- Predetermined Vol/Occ, Duration (3 min) thresholds for each meter
- Based on Field observation, tuning. No systematic procedure

Start up phase => Solid Green = 20-25 s, Yellow = 5 s
No Yellow during regular metering period
No signal (black) during Off-metering period
No coordination with Adjacent Intersection Signals
Each ramp has predetermined 6 cycles (Cycle 6 - most restrictive rate)
  Green: 2.0 - 2.5 s (Variable, Extended until a vehicle clears passage detect.)
  Red: 2 - 18 seconds
  Every 20 seconds, One Rate is selected from Local, Queue and Group metering
  If stop-bar detector or all loops are malfunctioning => Rate 1 (least restrictive)
For Two Lane Ramps
  Two meters have same signals: Simultaneous release of two vehicles
  If no vehicle detection at Demand detector => Extends Red
  If a vehicle is detected during Extended Red, then change to G after 1 s Red
Queue Override => Internal CODOT policy from the beginning (No queue spill-back)

Kwon

Metering Algorithm: Local Control with Group Coordination
+ Queue Override

Mainline Vol/Occ/min
→ Local Control
  - Predetermined Vol/Occ Thresholds
  6 cycles (rates)
→ Local Control Rate
→ Group Coordination
→ Local Rate
→ Queue Override
→ Final Rate

Queue detector Occ/min
→ Queue Control
  - Queue Occupancy Thresholds
  (15 - 80%)
→ Queue Rate
  Add 2 - 5 s Red if HOV detected

Kwon
Primary group coordination (upstream ramp rate restricted by one level)

Secondary group coordination (after all the ramps in primary group become critical)

Primary Group Coordination
when a Ramp in a group becomes 'Critical',
- either Local rate is Cycle 6 or in 'Queue Override' mode

If Rn is a Critical Ramp at time k,
then Rn+1 rate \(\Rightarrow\) One Level more restrictive than Rn+1 Local Rate after \(k + T(n, n+1)\)
where, \(T(n, n+1) = \text{Estimated Travel time from Rn+1 to Rn at time } k\)

If Rn is still Critical at the next update time, \(k+20\) s,
then Rn+2 also gets One Level more restrictive rate than its Local Rate after \(T(n, n+2)\)
where, \(T(n, n+2) = \text{Estimated travel time from Rn+2 to Rn at time } k+20\)
If all the Ramps in Group $i+1$ have 'Group Coordinated Rates' of Cycle 6 and $R_n$ is still Critical, then 'Secondary Group Coordination' starts.

Rate for $R_j$ = One level more restrictive rate than its Local Rate.

Continues 'Group Coordination' until all the ramps in upstream Group have coordinated rates, i.e., one level more restrictive rates than local rates.

If the Critical Ramp becomes Not Critical,

$\Rightarrow$ all the ramps go back to Local Control simultaneously.

Grouping $\Rightarrow$ Mostly based on Geometric Condition.

---

Queue Override

If Queue Rate is more restrictive than 'Local Rate' resulting from 'Local control' and 'Group Coordination'.

$\Rightarrow$ Increase Local Rate by one level through time until it reaches Queue Rate level.

At time $k$, Local Rate level = 5, Queue Rate level = 3
then Rate level at $k = 5 - 1 = 4$

time $k+1$, Local Rate level = 5, Queue Rate level = 3,
then Rate level at $k+1 = 5 - 2 = 3$

time $k+2$, Local Rate level = 5, Queue Rate level = 3,
then Rate level at $k+2 = 3$

* Local Queue Rate overrides Group Coordinated Rate.
Denver System

⇒ Represents ‘Heuristic’ Algorithm
  - Simple in nature, but ‘not-so-simple’ to implement
  - Needs to estimate variable ‘travel time’ to Critical Ramps
  - No quantified Target Objectives
⇒ From the beginning, ‘Queue Override’ has been CDOT Policy
  - “Ramp Queue should not extend to local street”
⇒ ‘Group Coordination’ can be less effective by Queue Override
⇒ No systematic “Benefit” analysis done yet
⇒ No coordination with adjacent intersection signals

⇒ Does not require ‘Capacity’ estimation
⇒ Queue Management priority
  - Less complaints by public
California (System Wide Adaptive Ramp Metering: Being installed)

SWARM rate calculation procedure

Step 1) Required bottleneck density at the current time step

\[ = \text{current density} - (\text{predicted density} - \text{saturation density})/ T \]

Step 2) Needed Volume Reduction at the detector station upstream of a meter

\[ = (\text{Local density} - \text{Required bottleneck density}) \times (\text{number of lanes}) \times (\text{Distance to next downstream ramp}) \]

Step 3) Metering rate = current ramp volume + (Volume Reduction)
San Diego Ramp Metering System

- 250 Meters with 4 Freeway to Freeway Meters (6 CCTV Cameras)
- Local Responsive Metering (Off-line coordination)
  - 30 sec. update with 1-min smoothed data (Single Loop at each Lane)
- Some ramps allow Two cars per Green
- No HOV by-pass
- No Queue override
- No Operator intervention in Ramp Meter Operation
- No Coordination with adjacent intersection signal
- No Video Wall at Control Room, which is shared by Patrol Dispatch, Maintenance and Traffic Operation groups

Starting/Ending Operations

<table>
<thead>
<tr>
<th>Starting Transition</th>
<th>Forced Operation</th>
<th>Ending Transition</th>
<th>Time</th>
</tr>
</thead>
</table>

Meter starts with Solid Green at the starting time of the Start Transition period until the measured mainline Vol/Occ warrants metering
- Each ramp has
  1 min Volume/Occupancy thresholds &
  3 min Volume/Occupancy thresholds
- During transition periods, compare previous 1 min and 3 min Vol/Occ data with thresholds
  (3 min thresholds are lower than 1 min threshold values)
- If Measured Data = Thresholds, then Yellow Warning Signal before Metering
  Starting rate = Rate 1 (Total 15 Rate Levels)
- Ending Transition: If measured data meets Ending Thresholds, Signal => Solid Green until the end of Ending Transition Period

Kwon
**Metering Rate Determination**

Each meter has Minimum and Maximum Rates
Min. Rate = 85% of Un-metered volume

System-wide restrictions
For One-Lane Ramp,
  One car per green: Min. Cycle = 6 sec. (720 vph)
  Max. Cycle = 15 sec. (240 vph)
  Green time = Min. 1.4 sec to until a vehicle hits passage detector
  No yellow signal

  Green time = Min. 3.2 sec. Until second car goes through yellow
  Yellow time = 2.2 sec.

**Metering Rate Determination (continued)**

Each Meter is assigned
- Min. Rate
- Max. Rate
  - 15 Interim Rates between Min. and Max. (Linear scale)
- dV (Volume Increment) and dOc (Occupancy Increment)

In Real Time, measure Mainline Volume/Occupancy from immediate upstream detector station:
- 30 sec. Data collection, 6-min. moving average
- \( V_{s,t} = \alpha \cdot V_t + (1 - \alpha) \cdot V_{t-1} \)

- If \( V_s, t >= V_s, t-1 + dV \) or \( O_s, t >= O_s, t-1 + dOc \)
  then go to Next Rate

Compare Rates from Volume and Occupancy Thresholds
Select More Restrictive Rate
Determination of Local Thresholds (Off-line preparation)

1) Segment downstream Boundary => Bottleneck
   * Bottleneck determination based on Geometry and Traffic Data
     (No written procedure, Engineering Judgement)

2) Determine Target Flow Rate at Bottleneck: QT
   * 95% of Operational Capacity, which can be maintained over
     significant period of time (90 minutes or so) for 9 out of 10 days
     that are free from both incidents and inclement weather

3) Based on QT, determine a Steady-State mainline flow rate profile, i.e.,
   Target Flow Rate at downstream of each ramp within each Segment
   assuming worst-case peak period flow rates of any uncontrolled feeder

4) Determine Most Restrictive Metering Rate for each ramp considering
   * Queue spill back to local streets, Equalization of ramp queue delays
   * Usually 15% below of unmetered discharge rate

5) Determine Least Restrictive Metering Rate

Volume (Occupancy) Control Thresholds: V & O control same at speed 50-60 mph
6) Mainline Flow Rate at Detector J, Qj,m, which should cause Most Restrictive
   Rate at Ramp J (Rate 15)
   = Bottleneck Target Flow Rate QT - Most Restrictive Rate at Ramp J
   * Also determine corresponding occupancy value to Qj,m

7) Mainline Flow Rate at Detector J, Qj,l, which should cause Least Restrictive
   Rate at Ramp J (Rate 1)
   = Bottleneck Target Flow Rate QT - Least Restrictive Rate at Ramp J
   * Also determine corresponding occupancy value to Qj,l

8) Calculate Volume Increments, dV, and dQc, to determine Interim Rates 2 - 14

Kwon
"Rate Linking"

At time $t$, Rate Level at $J+1$, $R_{j+1,t}$, is given to upstream Ramp $J$.

Then at $t+1$, Rate Level at Ramp $J$ cannot be less than $R_{j+1,t}$.
Rate Level at $J = \max \{ R_{j+1,t}, \text{ Local Rate Level for } J \text{ at } t \}$
I.e., Upstream ramp applies at least equal or more restrictive rate level
than downstream ramp at next time interval.

* Rate Level $= 1 - 15$, $15 \Rightarrow$ Most Restrictive Rate Level

Critical Review of Ramp Metering Systems
(Seattle System)

Eil Kwon

Brief Review of Minnesota (MnDOT/ICTM) Algorithm

Seattle Metering System
1) Bottleneck Algorithm
2) Fuzzy Metering
Mn/DOT Algorithm

\[ A + M + U = B + X + S \]
\[ Mt = E_j - (At + Ut) + Xt + St \]

Rate 1: \( Qt,i + 1.5 \Rightarrow \) Sum Qt,i,1 = Mj,1

<table>
<thead>
<tr>
<th>Mj,2</th>
<th>Mj,3</th>
</tr>
</thead>
<tbody>
<tr>
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<td>5</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\[ Mi, \text{t} \]

ICTM Algorithm

\[ Q_i = Qt_i (1 + g_i + b/p_i)(1-a_i/p_i) \]

where

\[ b = \{N - \sum [Qt_i(1+g_i)]/ \sum Qt_i/p_i \} \]
\[ N = B - A - U + X + S \]
\[ g = \text{Ramp queue factor} \]
\[ S = \sum [Q_i - Qa_i] \]
\[ a = \text{Occupancy factor (?)} \]
\[ p = \text{Ramp bias value} \]
Issues with Minnesota Algorithm

Strong dependency on Accurate Data in Real Time
  e.g., A station, Ramp volumes,
  Variations with Occupancy measurements

Bottleneck "Capacity" and Location

Metering for Congested Traffic
  => Determination of Occupancy Thresholds

Seattle Metering System

Every 20 seconds, use 1-minute data
  (Volume, Occupancy, Speed)
Detector spacing = 1/4 - 1/2 mile
25% of total loops => Speed loops
**Local Metering**

![Graph showing Veh/min vs Occ (%)]

**Bottleneck Algorithm**

If Section k 'stores vehicles', i.e.,

\[(\text{Input Sum})_k - (\text{Output Sum})_k = SV_k > 0\]  
\[R_{j,k}(t+1) = R_j(t) - \left[ \frac{WF_{j,k} + SV_k}{\text{Sum of WF of all ramps for k}} \right]\]

If \(SV_{k-1} > 0\), i.e., Section k-1 also 'stores' vehicles

\[R_{j,k-1}(t+1) = R_j(t) - \left[ \frac{WF_{j,k-1} + SV_{k-1}}{\text{Sum of WF of all ramps fpr k-1}} \right]\]
Queue Adjustment in Bottleneck Algorithm

If Queue detector 1 Occ > Thres for Time1 (2 min) then add 1-2 veh/min
If after Time2 (3-4 min), still Occ > Thres then add 4 veh/min
If any Advance Queue detector Occ > A-Thres then add 5 veh/min

Bottleneck Algorithm Concept

Does not require “Capacity” explicitly
Tries to identify “Bottleneck” section in real time

However,

“Stored Volume” in a section => Key factor affecting rates
i.e., (Total Input - Total Output)

Due to malfunction or missing detectors
Error in volume data is often higher than Storage Rate

Queue adjustment ➔ Mainline congestion ➔ Restrictive Metering
Fuzzy Metering Algorithm

Fuzzy Logic Control

Use natural linguistic variables and tries to mimic heuristics of Human Reasoning by employing multiple Rules simultaneously.

1) Fuzzification (Fuzzy classes, membership function)
   => Convert Crisp variables into Fuzzy classes
   e.g.,

   ![Fuzzy Classes Diagram]

   15% => e.g. rule to be true 0.2
   Set variable, e.g. VS

2) Rule Development and Evaluation

   ![Rule Development Diagram]

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight</th>
<th>Premise</th>
<th>Conclusion</th>
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</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>OC_B</td>
<td>S</td>
</tr>
</tbody>
</table>

   If Crisp occupancy 16% => 0.2 for VB => Rate is VS to a degree of 0.2
   0.6 B Rate is S to a degree of 0.6
3) Defuzzification

<table>
<thead>
<tr>
<th>Rate</th>
<th>VA</th>
<th>Premise</th>
<th>Rule Outcome</th>
<th>Min</th>
<th>Max</th>
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<td>VS : 0.2</td>
<td>C1^*</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>OC_B</td>
<td>S : 0.6</td>
<td>C2^*</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Rate (0-1.0) = ([Total OV] / [Total OC]) (Min \+ 1)

E.g., Rate = 0.26, Min = 7 veh/min Max = 17 veh/min
Then final rate = 7 + (17-7) * 0.26 = 9.6 veh/min

Fuzzy Metering

Does not require Freeway System Modeling
Considers many factors simultaneously
- Multi-Objective Heuristic Optimization
- Less sensitive to Detection Errors

Requires lots of parameter tuning in the field
Field evaluation results at Seattle
=> Similar performance on Mainline, but better management of Ramp Queue
Virginia Ramp Metering System

Total 26 meters (16 at I-395, 10 at I-66)

- Volume/Occupancy data from One single loop at mainline
  (Rate updated every 1 minute: New system => 10 sec.)
- Two cars per Green (Two meters have same signals)
- Metering Algorithm
  => Link-based Section-wide control
  => Queue dump mode when Queue Occupancy (QO) > 25%
    (either Turned off or pre-defined maximum rate until QO < 25%)
- Automatic turn on/off
  => Measured Link Input Volume > or < pre-set thresholds
    (No required time duration)
Link-based Section-wide control

One Section has up to 10 links
For every 1 minute, for each link in a Section, determine
Predicted Arrival Volume (PRD) and
Maximum Permissible Link Volume (RDL)

Metering Rate for Link $i = PRD(i) - RDL(i)$

Predicted Arrival Volume for link $n$: $PRD(n)$

- $PL(1)$: Measured mainline volume on link 2 (after exit ramp)
- $RRVOL(2)$: Measured on-ramp volume on link 2
- $QE(2)$: Predicted Exit volume at link 2

Predicted Demand just upstream of link 3 on-ramp: $PRD(3)$

$PRD(3, t) = PL(2, t-1) + RRVOL(2, t-1) - QE(3, t)$

where, $QE(3, t) = QE(3, t-1)$

$PRD(3, t) = \max\{PL(3, t-1), [PL(2, t-1) + RRVOL(2, t-1) - QE(3, t)]\}$

$PRD(n, t) = \max\{PL(n, t-1), [PL(n-1, t-1) + RRVOL(n-1, t-1) - QE(n, t)]\}$
Maximum Permissible Volume for Link n: RDL(n)

Q(n): Maximum permissible volume on link n not to exceed the capacity of downstream link n+1

p(n): Fraction of volume remaining on the mainline after vehicles exited through off-ramp in link n = PL(2)/[PL(2) + X(2)]

where: PL(n): Measured mainline volume on link n
RL(n): Minimum metering rate for on-ramp in link n

\[ p(3)Q(2) + RL(3) = RDL(3) \Rightarrow Q(2)_1 = \frac{[RDL(3)-RL(3)]}{p(3)} \]
\[ p(3)Q(2) + Eqv(3)RL(3) = F(3) CC(3) \Rightarrow Q(2)_2 = \frac{[F(3)CC(3)-Eqv(3)RL(3)]}{p(3)} \]
\[ RDL(2) = \text{Min} \{ Q(2)_1, Q(2)_2, Q(2)_3 \} \]

RDL(n-1) = \text{Min} \{ [R(2)L(n)-RL(n)/p(n), F(n-1)C(n-1), [F(n)CC(n)-Eqv(n)RL(n)]/p(n)] \}

Control Section

Estimation sequence of Maximum Permissible Link Volume (RDL)

Prediction sequence of Arrival Link Volume (PRD)

Metering rate for link n (1 min update)
= RDL(n) - PRD(n)
Metering Rate for Link n: \( RC(n) = RDL(n) - PRD(n) \)

Final Metering Rate is determined by considering Merging Capacity, \( CC(n) \)
\[ PRD(n) + Eqv(n) \cdot RC(n) = F(n) \cdot CC(n) \]

\[ RC(n) = \text{Min} \{ [RDL(n) - PRD(n)], [F(n) \cdot CC(n) - PRD(n)]/Eqv(n) \} \]

Also, \( \text{Min. Rate} \leq RC(n) \leq \text{Maximum Rate (Queue dumping rate)} \)

\( \text{Min. Rate} : 200 - 250 \text{ veh/hr} \)
COMPARATIVE ANALYSIS OF OPERATIONAL ALGORITHMS
FOR COORDINATED RAMP METERING

January 2001

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Department of Civil Engineering

University of Minnesota

Project Tasks

- Study Detailed Procedures of Coordinated Metering Algorithms currently in Operation.

- Analyze Performance Patterns of 3 selected algorithms through Sensitivity Analysis using Macroscopic Simulation
  - Under same geometry and traffic demand
  - Performance variation responding to key parameter changes
    => Compare Performance Patterns
    => Identify Desirable Features of each algorithm

- Development of an Alternative Metering Approaches
Current Operational Algorithms for
On-Line Coordinated Metering

• Denver, Colorado \implies Incremental group coordination

• Virginia (Washington, D.C), California (SWARM), Minnesota
\implies Explicit section-wide coordination for
Bottleneck Flow Maximization

• Seattle, Washington \implies Fuzzy Logic-based Implicit coordination

* San Diego \implies Local Control based on Off-Line Coordination
* Minnesota and San Diego \implies Only systems without Queue Override

Selected Algorithms for Comparative Analysis: Denver, Seattle, Minnesota
Denver Algorithm

Starts with Local Control: 20 sec. Vol/Occ.

--- Primary group coordination (upstream ramp rate restricted by one level)

----- Secondary group coordination
(after all the ramps in primary group become critical)

Queue Control overrides Group Coordination
Performance Analysis of Denver Metering Algorithm

Key parameters: Local Volume/Occupancy Thresholds
Queue Occupancy Thresholds

Queue Occupancy Thresholds in Denver Metering

Rate 1 70
Rate 2 60
Rate 3 50
Rate 4 40
Rate 5 30
Rate 6 20

Rate Level

Queue Occupancy %
Different Queue Occupancy Threshold Policies in Denver Algorithm
Effects of Volume Thresholds in Denver Algorithm (No Queue Override)

Effects of Queue Occupancy Thresholds in Denver Algorithm (Volume Thresholds: 1875-2275, Day 1)
Effects of Queue Occupancy Thresholds in Denver Algorithm
(Volume Thresholds: 1875-2275, Day 2)

1st Tuesday

2nd Tuesday
Seattle Fuzzy Metering

<table>
<thead>
<tr>
<th>Rate</th>
<th>Signal</th>
<th>IN (Green)</th>
<th>OUT (Red)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>OC_VB</td>
<td>VS</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>OC_B</td>
<td>S</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>DO_VB/DS_VS</td>
<td>VS</td>
</tr>
<tr>
<td>11</td>
<td>2.0</td>
<td>QO_VB</td>
<td>VB</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td>AOO_VB</td>
<td>VB</td>
</tr>
</tbody>
</table>

Every 20 second update with 1-minute data

Fuzzy Classes and Membership Functions

If 'Crisp' occupancy 15% => 0.2 for VS => Rate is VB to a degree of 0.2
0.6 S Rate is B to a degree of 0.6
Implicit Coordination of Multiple Ramps in Fuzzy Metering

No Explicit 'Metering Section' structure

Simulation of Fuzzy Metering Algorithm

- Examine Performance Sensitivity with respect to Weight changes in Key Rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight</th>
<th>Premise</th>
<th>Rule Consequence</th>
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<tr>
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<td>VB</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td>AQO_VB</td>
<td>VB</td>
</tr>
</tbody>
</table>

- Use Same Fuzzy Classes and Membership Functions as in Seattle
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Effects of Combined Queue Weights (Day 2)

(Primary Queue: Rule 11, Advance Queue Rule 12)

Day 1

Effects of Rule 10: DO_VB/DS_VS: Day 2
(QW, AQW: 1.0, 2.0)

Day 1
MnDOT Metering

=> Zone-wide Explicit Coordination with Consideration of Downstream Conditions

Bottleneck

\[
\begin{array}{c}
i-1 \\
\downarrow \\
A_i \\
\uparrow \\
i \\
\downarrow \\
B_i \\
\uparrow \\
i+1
\end{array}
\]  

Volume Thresholds => Zone-wide, Bottleneck-capacity based Occupancy Thresholds => Individual Ramp-ramp based
Control Options in Minnesota Algorithm
- Zone/Occupancy Control,
- Zone-based Volume Control,
- Ramp-based Occupancy Control

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Performance Variation wrt Occupancy Threshold Changes (No Zone Control)
Comparison of Control Options: Day 1 (6 rates)
Performance Comparison of Denver, Fuzzy and Minnesota Algorithms

- Best case of each algorithm from Limited Simulations
  - Due to Project Time limitations,
    No Exhaustive Search for Optimal Parameters was done.
- Focus on Comparing Performance Patterns, Not Absolute Values
Performance Comparison of Denver, Fuzzy and Minnesota

**Day 1**

- Denver: Queue Over. (70-30)
- Fuzzy (Q:1, AG:2)
- MnDOT: Occ(10-30)
- Main Veh: Hrs
- Ramp Veh: Hrs
- Total Veh: Hrs
- Main Cong. Veh: Hrs
- Main Veh: Miles

**Day 2**

- Denver: Queue Over. (70-30)
- Fuzzy (Q:1, AG:2)
- MnDOT: Occ(3-30)
- Main Veh: Hrs
- Ramp Veh: Hrs
- Total Veh: Hrs
- Main Cong. Veh: Hrs
- Main Veh: Miles
SUMMARY

Denver Algorithm

\[ \Rightarrow \text{Incremental Group Coordination with Explicit Queue Override} \]

- Consistently resulted in more congestion and less vehicle-miles on mainline
- Lower Average Ramp Vehicle-hours than others
- Does not Require Link Capacity or pre-determination of Bottlenecks
- Negative effects of Queue Override on Congestion Management

\[ \Rightarrow \text{‘No Queue Override’ resulted in less congestion with compatible mainline vehicle-miles} \]
Seattle Algorithm

- Fuzzy-logic based Implicit Coordination with Explicit Consideration of Ramp Queue conditions
- More mainline vehicle-miles than Minnesota, but more congestion
- Less Ramp Vehicle-hours during peak-period than Minnesota algorithm
- Does not require link capacity or pre-determined Bottleneck locations
- On-Line adjustment of system performance possible with Rule Weights
- Tries to balance automatically Ramp Queue and Mainline Congestion
  --> Resulted in Concentrated Congestion Patterns during peak-periods
- No ‘Systematic Optimal’ method to determine Best Set of Fuzzy parameters such as Membership functions and Rule weights
  --> Currently ‘trial and error’ with real data

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Minnesota Algorithm

- Explicit Section-wide coordination approach without Queue Override
- Better in terms of managing mainline congestion
  --> Less congested vehicle-hours and more evenly distributed traffic
- But More Number of Ramps with High Vehicle-hours than other algorithms
- Ramp vehicle-hour distribution
  --> Significant variations from zone to zone
- Requires Accurate estimation of Bottleneck Capacity and Reliable detection at Key locations, e.g., A-stations
- Occupancy-Only-Control consistently resulted in the performance pattern that accommodates more vehicles during metering period, i.e., less amount of ramp vehicle-hours than Volume/Occupancy control

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SUMMARY COMPARISON

- Both in Denver and Seattle Fuzzy algorithms, Ramp Queue management is heavily considered in determining metering rates.
  => 'Compromised' vs 'Absolute Optimal Management'

- Fuzzy and Minnesota algorithms perform significantly better than Incremental Coordination approach in managing Mainline Traffic

- But Denver algorithm produced consistently Lower Ramp Vehicle-hour patterns than others mainly because of its Explicit Queue Management policy.

- Minnesota algorithm, adopting Explicit Zone-wide coordination, shows clear advantage over Fuzzy algorithm in terms of mainline management, however, Fuzzy resulted in less ramp vehicle-hour patterns during peak-congestion period.
  
  Minnesota = Zone-wide control + Individual ramp control (downstream)
  Seattle Fuzzy = Individual ramp control (local upstream, downstream, Queue)

SUMMARY COMPARISON (Continued)

- More Ramps with Minnesota algorithm have High Vehicle-hours than other algorithms
  
  Minnesota => Zone to Zone variation
  Fuzzy => Ramp to Ramp variation

- Both Denver and Fuzzy algorithms try to identify Bottlenecks in Real Time
  => Do not require pre-determined Bottleneck locations and Capacity values

- Structure of Fuzzy algorithm allows flexible Real-time adjustment depending on management objectives and system constraints,
  => Change Rule Weights for ramp queue and/or downstream conditions
  => Less sensitive to detector malfunction
Enhancement of Minnesota Algorithm

Short-term
1) Ramp Queue-management
   #1: Fixed Queue-Occupancy threshold w/ Incremental adjustment
   #2: Queue-Thresholds => Queue Rate, comparison with System Rate
2) Incorporation of Ramp Queue condition into Metering Rate calculation
   Real time, frequent adjustment of system parameters
   Dynamic zone with Moving Bottlenecks, Non-capacity based
   Adaptive system-wide coordination

Long-term: Corridor Management
   => Integrated control of Freeway Ramps and Intersections
   => Diversion management with Advanced Traffic/Incident Information
   => Spatial measurements, e.g., travel time, origin/destination

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Nested Zone Performance (1st Tuesday)

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Issues with Future Metering

- Policy Issue
  - "System Efficiency" vs "Human-centered"
    Balanced management of Ramp Queue and Mainline Congestion
    "Maximum Flow" vs "Safety and Incident Management"
  - "Control" vs "Information/Guidance"
  - Integrated Management of Freeway and Arterial Network

- Technical Issue
  - New Freeway System Performance Index Reflecting different weights on Ramp and Mainline vehicle-hours
  - Automatic Performance Monitoring/Quantification, Feedback, Adjustment
  - Real-time Identification of Effective Metering Period
    Meter Turn On/Off Conditions
    Congested Freeway without Alternative Routes
  - Capacity vs Non-Capacity-based Approaches
  - Point Detection vs Section-wide or Spatial Measurements
Development of an Alternative Metering Approach

- Requirements:
  Adapt to continuously changing Roadway/Traffic conditions
  - Demand/Capacity variation
  Less sensitive to Detector malfunction
  Work with existing detection system
  Easily incorporated into current control structure

- Basic approach
  Measurement-based ‘Direct Adaptive Control’
  Real time Identification of ‘Control-Traffic state’ Relationship
  Single control rule for both uncongested and congested traffic
Zone-wide Congestion Index (CI)

- 'Spot Density'-based CI with Volume/Speed detection
  \[ K_{i,t} = \text{Sum of } w_{i,j} \times k_{i,j} \]

- Volume/Occupancy-based CI
  \[ C_{i,t} = \text{Sum of } w_{i,j} \times [(Vt + Ot)_{i,j} / (Vt + O_{\text{max}})_{i,j}] \]

- Possible to estimate 'Zone-wide Queue Congestion Index'
  \[ Kq_{i,t} \text{ or } Cq_{i,t} \]

Coordination of Multiple Zones with Fuzzy-logic

\[ K_{d,i}(t+1) = K_{d,i} \times \text{Beta}_i(t+1) \]

\[ 0 \leq \text{Beta}_i(t+1) \leq \text{Beta}_{\text{max}}. \]

Determine \( \text{Beta}_i(t+1) \) using Fuzzy Logic with
\[ K_{i}(t), K_{i+1}(t) \text{ and } K_{q,i}(t) \]
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<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Weight</th>
<th>Premise</th>
<th>( \beta ) Outcome</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>ZONE_K VB or ZONE_C VB</td>
<td>VS</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>ZONE_K B or ZONE_C B</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>ZONE_K M or ZONE_C M</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>ZONE_K S or ZONE_C S</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
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<td>VS</td>
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<td>9</td>
<td>1</td>
<td>NEXT_ZONE_K S or NEXT_ZONE_C S</td>
<td>B</td>
</tr>
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<td>10</td>
<td>1</td>
<td>NEXT_ZONE_K VS or NEXT_ZONE_C VS</td>
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</tr>
<tr>
<td>11</td>
<td>1</td>
<td>QUEUE_K VB or QUEUE_C VB</td>
<td>VB</td>
</tr>
</tbody>
</table>

*VB = Very Big, B = Big, M = Medium, S = Small, VS = Very Small*
Zone-wide Adaptive Control

- Each meter has Minimum and Maximum Rates
- Common Rate Level is applied to all ramps in a zone, e.g., 1 - 6
  \( 1 \Rightarrow \text{Min. Rate Level}, \ 6 \Rightarrow \text{Max. Rate Level} \)
- Determines Zone-wide Rate Level
  \[ \text{Min. Rate Level} \leq R_{\text{d},i}(t) \leq R_{\text{max}}(t), \ \text{and} \ \hat{r}(t) \leq \text{Max. Rate Level} \]
- Adaptive Rule: \( \Rightarrow \) Tries to make 'Zone-wide CF' close to 'Desired Level of CF'
  \[ K_{\text{d},i}(t) \text{ or } C_{\text{d},i}(t) \Rightarrow K_{\text{d},i} \text{ or } C_{\text{d},i} \]

\[ \frac{R_{\text{d},i}(t)}{R_{\text{d},i}(t)} \leq 1.0 \]

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Zone-wide Adaptive Metering with Fuzzy Coordination

Maximize total system throughput (veh-miles)
while minimizing total system delay (veh-hours)

• Treat 'zone' as a control unit for system-wide coordination
  ⇒ Apply Fuzzy-logic for Coordination of multiple zones
• Use zone-wide 'Congestion Index' estimated with point measurements
• Does not require 'Link Capacity' estimation
  ⇒ Use 'Desired Density or Congestion Level' for each zone
• Initial version ⇒ Fixed zone structure using current zone configuration
  (working on Dynamic zone module)

Performance Evaluation of New Algorithm with Simulation

16-mile section of 169 Freeway as Sample Section

Use current Mn/DOT zone structure of the 169 freeway
(same Minimum and Maximum Rates for each ramp)

Desired zone-wide density : 45 - 57 vpm
  congestion index: 0.4 - 0.5

Zone-wide rate level: 1 - 6

Beta : 0.7 - 1.3
Simulation under normal condition (capacity 2200 vphl)

<table>
<thead>
<tr>
<th>No Metering</th>
<th>MN-DoT</th>
<th>Desired Congestion Index ( (C_u) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( C_u = 0.4 ) ( 0.45 ) ( 0.5 )</td>
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<tr>
<td></td>
<td>30 sec</td>
<td>20 sec</td>
</tr>
<tr>
<td>airline Veh-miles</td>
<td>330675</td>
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<tr>
<td>Veh-hours</td>
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<td>8727</td>
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<tr>
<td>Delay</td>
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<td>19997</td>
</tr>
<tr>
<td>amp Veh-miles</td>
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<td>23661</td>
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<tr>
<td>Veh-hours</td>
<td>824</td>
<td>1668</td>
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<tr>
<td>Delay</td>
<td>372</td>
<td>11760</td>
</tr>
<tr>
<td>Total Delay</td>
<td>6289</td>
<td>3175.77</td>
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*Control time interval*
<table>
<thead>
<tr>
<th>No metering</th>
<th>MNDot</th>
<th>Desired Density ($K_d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K_d = 45$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 sec.</td>
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<tr>
<td>airline</td>
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<tr>
<td>Total Delay</td>
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<td>3175.77</td>
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</table>

Simulation under Reduced Capacity (1800 vphl)
Sensitivity with respect to Weights on Queue Congestion Index