Real-Time Metering Algorithm for Centralized Control

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In response to growing freeway congestion problems in the Seattle area, the Washington State Department of Transportation (WSDOT) initiated a ramp-control program in 1981 as part of a regionwide transportation system management effort. The ramp-metering system is a computer-based, distributed intelligence system that consists of field-located microprocessors and a centralized computer system. It is an integrated, traffic-responsive metering system. The system uses an algorithm that calculates metering rates in real time based on systemwide traffic conditions. The algorithm is simple in its approach but very effective in its application. The system has proven to be effective in a series of ongoing evaluations. In this paper, the WSDOT real-time ramp-metering algorithm is described. First a brief description of the Seattle area freeway system and an overview of the development of the ramp metering system are provided. The components of the surveillance, control, and driver information system are then described, followed by a description of the physical elements of the ramp-metering system. After the real-time algorithm used, the limitations of the algorithm, and the advantages of the algorithm are described, the results of an ongoing evaluation effort are presented. Finally, further actions being planned are described.

In response to growing freeway congestion problems in the Seattle area, the Washington State Department of Transportation (WSDOT) initiated a ramp-control program in 1981. The ramp-control system is one element of a surveillance, control, and driver information (SC&DI) system that is part of a regionwide transportation system management effort called FLOW. Other FLOW system elements include park-and-ride lots, freeway flyer stops, high-occupancy vehicle (HOV) lanes, operation of an arterial control system, and operation of a reversible lane control system. The SC&DI system incorporates ramp control, closed circuit television (CCTV), electronic surveillance, a variable message sign system, a highway advisory radio system, a link to the computerized arterial control system, and a graphic display system to aid in driver information reports given to commercial radio stations.

The purpose of this paper is to describe the WSDOT real-time ramp-metering algorithm. First, a brief description of the Seattle area freeway system and an overview of the development of the ramp-metering system are provided. The components of the SC&DI system will then be described, followed by a description of the physical elements of the ramp-metering system. After the real-time algorithm used, the limitations of the algorithm, and the advantages of the algorithm are described, the results of an ongoing evaluation effort are presented. Finally, further actions being planned are described.

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DESCRIPTION OF THE SEATTLE FREEWAY SYSTEM AND GEOGRAPHY

The combination of the Seattle area's population with its geography creates problems in providing mobility on the freeway system. The Seattle area contains roughly 2 million people, or about 47 percent of Washington State's population. Unfortunately, the physical characteristics of the area have resulted in very few parallel alternative routes that motorists can use to bypass congestion. Seattle is configured in a narrow hourglass through the downtown area (Figure 1). The length of the hourglass runs north-south, with Lake Washington to the east and Puget Sound to the west. Four major freeways serve the area: I-5 runs north-south through the Seattle area; I-405, a loop freeway that bypasses Seattle, also runs north-south through the suburbs east of Lake Washington; I-90 begins in downtown Seattle and runs east-west across Lake Washington; and finally, State Route 520 runs east-west and is the only other route across Lake Washington. While there are other routes in the area, these four present the toughest issues for traffic management. To further the challenge, the regional metropolitan planning organization, the Puget Sound Council of Governments, has adopted a transportation plan that includes no new highway segments through the year 2000. As a result, the Washington State Department of Transportation has spent a great deal of effort to operate its freeways most efficiently.

HISTORICAL DEVELOPMENT OF THE EXISTING SYSTEM

The Washington State Department of Transportation is now in its seventh year of operating a ramp-control system in the Seattle area. The metering system uses an on-line, centrally controlled algorithm that calculates metering rates based on systemwide traffic conditions.

The formulation of the Seattle area's ramp-control system began in 1968 with a preliminary planning effort. With the completion of the design report for the I-5 portion of the system in 1973, WSDOT developed a series of contracts, which led to the staged implementation of the existing system. The first of these contracts involved purchasing a computer and software to accumulate data from electronic surveillance sta-

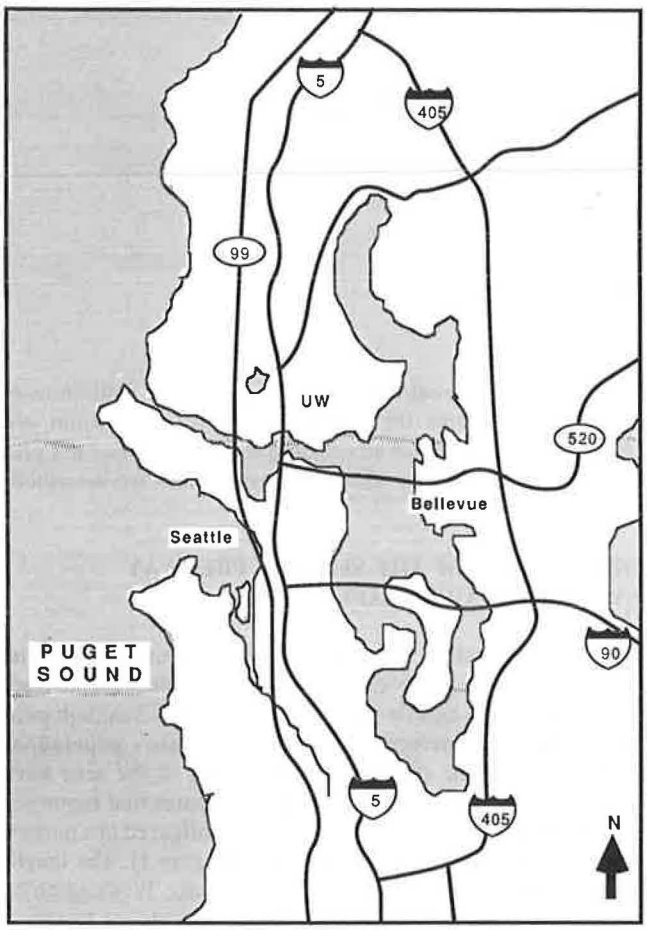

FIGURE 1 Seattle freeway system.

tions. (This computer also acts as the central master for an arterial signal control system.) Later contracts involved installing communication cable along the median of I-5, installing detector loops in the roadway, providing and installing data accumulators and cabinets, making geometric improvements to the roadway, providing and installing an improved closed circuit television system, and building an extension to the Traffic Systems Management Center (TSMC) to house the computers, peripheral equipment, and CCTV monitors.

In early 1979 WSDOT contracted to tie all these components together for an operational ramp-control system. The contract purchases included hardware and software for the central ramp-control computer, all central peripherals, and all field electronics for ramp control. The ramp-control system began operation on September 30, 1981. The initial system included 18 controlled ramps (*1*).

Since the initiation of the system, additional contracts have added six ramps to the system, updated and translated the ramp-controller software to Type 170 controllers, added data accumulation stations, and added cameras to and updated the CCTV system.

SYSTEM COMPONENTS

The Traffic Systems Management Center controls the SC&DI system, which is made up of the following eight components:

1. A closed circuit television system is used to verify incidents and report traffic conditions to local commercial radio stations. It comprises 34 color cameras, which cover 25 miles of freeway. It is controlled by a software switching system, which operates from a touch screen TV. Through the touch screen, the operator selects any combination of cameras and dwell time to appear on two sequencing monitors. All cameras have pan, tilt, and zoom functions. These functions are controlled through two additional monitors.
2. Induction loop detectors, embedded in the roadway, collect real-time volume and occupancy data. Currently just more than 900 loops are located on I-5, I-90, I-405, and SR 520. All mainline loops are 6 ft by 6 ft.
3. Seventy traffic data stations collect volume and occupancy data from the loop detectors and then transmit the data to the TSMC central computers.
4. Twenty-four ramp controllers perform the same data collection function as the traffic data stations, but they also meter ramps. Sixteen ramps are currently metered during the morning peak period, and seven ramps are metered during the afternoon peak. These include one dual-lane metering location and one freeway-to-freeway meter. Eleven of these 23 ramps have HOV bypass lanes.
5. A central computer system collects volume and occupancy data from the traffic data stations and the ramp controllers. The computer then uses this information to determine individual metering rates for each ramp based on local conditions and system capacity constraints.
6. Through color coding, a graphic display system shows various levels of congestion on I-5, I-90, I-405, and SR 520. This system is used extensively in ramp metering and also in reporting traffic conditions to the local radio stations. The information for the graphic display is obtained from the traffic data stations and ramp controllers, processed by the central computer, and output to color monitors.
7. Ten fixed-location variable message signs (VMSs), all electromagnetic flip disk, are controlled by a central system at the TSMC. Four of these signs are used on a 24-h basis to inform motorists approaching the north entrance to the I-5 express lanes of the lanes' status (open or closed). The other six signs warn motorists of downstream accidents, construction, or maintenance work. Four portable flip disk VMSs are also available to provide information on construction and maintenance projects and on major incidents.
8. The Highway Advisory Radio system consists of six low-powered radio transmitters. These also advise motorists of accidents, construction, or maintenance work.

RAMP-METERING SYSTEM

The ramp-metering system is a computer-based, distributed intelligence system that consists of field-located microprocessors and a centralized computer system.

Existing Field Equipment

The field-located equipment consists of both ramp controllers and traffic data stations. Both provide electronic surveillance through induction loop detectors embedded in each lane of the roadway. The loops are scanned by the microprocessors

60 times a second. Volume and occupancy data are then transferred to the central computer once every second.

Several validity checks are made in the field to determine the accuracy of the loop information. A loop actuation of less than 1/15 sec is ignored. Less than a 1/15-sec drop in presence is also ignored. The controller interprets this as a single actuation. Any volume count of more than two vehicles in a second is indicated by an error message sent back to the central computer. Although this check does not necessarily screen all bad data, it does cut down significantly on bad data transferred to and then used by the central computer.

Both the traffic data stations and ramp controllers provide the same traffic data accumulation functions. In metered sections, the ramp controllers and traffic data stations are spaced at 1/4- to 1/2-mile intervals. In other freeway sections, spacings range from 1/2 to 1 mile. The ramp controllers are located at interchanges and are capable of sampling the larger number of loops often associated with an interchange. The ramp controllers also perform the ramp-metering functions and gather and transmit alarm and failure information. The data accumulators are located between interchanges and only gather and transmit volume and occupancy data to the central computer.

If communication between the central computer and the ramp controller is lost, the ramp controller is able to continue metering with an occupancy control algorithm based on local conditions or based on a time-of-day table. However, while metering at any individual location is not interrupted, the coordination of the system as a whole is lost.

The original hardware installed in the field included Safetran 1610 controllers for ramp metering. The data accumulators used hardware-modified Type 170 controllers and some specially built microprocessors. However, maintenance and replacement of this equipment have been extremely difficult. As a result, all new controllers are off-the-shelf Type 170.

Central System

The central computer system is made up of two Perkin-Elmer 7/32 minicomputers. A high-speed data link ties the two machines together. One of the 7/32s, the Central Traffic Control Master (CTCM), communicates with the data accumulators. The second 7/32, the Video Display System (VDS), communicates with the ramp controllers and controls the ramp-metering system. The VDS system also drives the color graphics system, which displays various levels of congestion using color coding and is based on 1-min averages of loop occupancies. All volume and occupancy data are shared between the two systems every 20 sec via the data link. The data link also keeps the clocks of the two systems synchronized.

Communication System

Half of the ramp controllers and data accumulators communicate on a state-owned twisted-pair cable that runs along 17 miles of I-5. All other data communications are over dedicated telephone circuits. Ramp controllers communicate at 1200 baud, and the data accumulators communicate at 300 baud. Frequency shift keying is used in all communications.

THE ALGORITHM

The unique aspect of the ramp-control system is its on-line metering algorithm. The most significant aspect of the algorithm is the system, or "bottleneck," metering rate calculation. The algorithm was developed in 1978 in a cooperative effort between WSDOT personnel and their consultant, H. W. Lochner. The description of the algorithm that follows will use terminology found in the 1985 FHWA *Traffic Control Systems Handbook* (*2*). This terminology will minimize any ambiguity in the description and flow diagrams used. Although this version of the handbook was not published at the time the algorithm was developed, the algorithm fits nicely into the framework described.

The algorithm used in the Seattle system is, in the terminology of the handbook, an integrated, traffic-responsive metering algorithm because metering rates are calculated in real time based on system as well as local capacity conditions. In addition, queuing conditions on the ramps are also considered in the final calculation of metering rates. In effect, the metering algorithm has three components: calculation of metering rates based on local conditions, calculation of metering rates based on system capacity constraints, and adjustment to the metering rates based on local ramp conditions. A generalized flow diagram of the algorithm is presented in Figure 2. In the Seattle system, metering rates are calculated for each ramp every 20 sec based on 1-min accumulations of volume and occupancy. All flow rates and metering rates are expressed in vehicles per minute (vpm), and occupancy is truncated to the nearest tenth of a percent.

Local Metering Rate

One method of calculating metering rates that are based on local conditions is traffic-responsive metering using occupancy control. According to the handbook, predetermined metering rates are selected on the basis of occupancy levels upstream of the given metered ramp. Historical data are collected from the given data station location. These data are used to determine approximate volume-occupancy relationships at capacity. Metering rates are then calculated from the volume-occupancy relationships to allow ramp volume to make up the difference between the estimated capacity and the estimated real-time upstream volume. The handbook implies that the metering rate is selected from a predetermined, finite set of discrete metering rates.

The handbook's outline of the process adequately describes the local metering rate calculation employed in the Seattle system. However, the metering rate is calculated from straight-line interpolation between discrete points on the occupancy-metering rate curve that is developed from the volume-occupancy curve for the upstream mainline station corresponding to the given metered ramp (see Figure 3). If the real-time measurement of occupancy is P_i, and $P_x < P_i \leq P_y$, where P_x and P_y correspond to adjacent discrete points on the occupancy-metering rate curve (P_x,A_x) and (P_y,A_y), where $P_x < P_y$ and $A_x > A_y$, then the metering rate is calculated as

$$A_i = A_x + \frac{(A_y - A_x)}{P_y - P_x}(P_i - P_x) \quad (1)$$

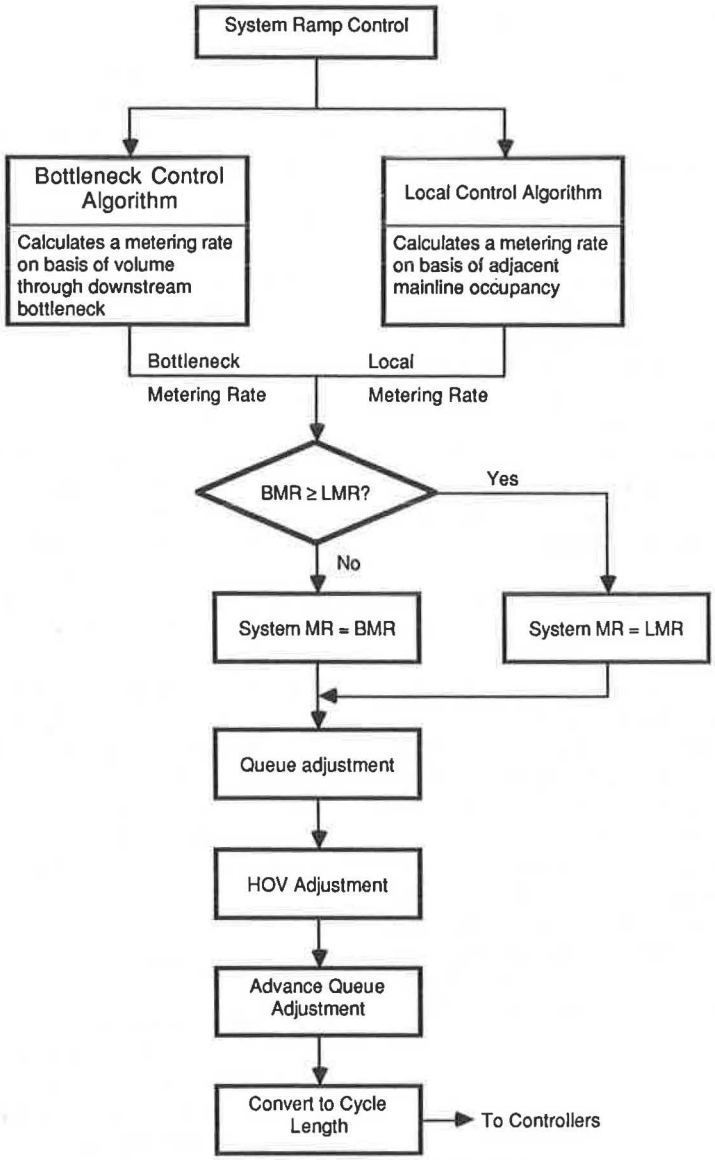

FIGURE 2 Generalized ramp-metering algorithm.

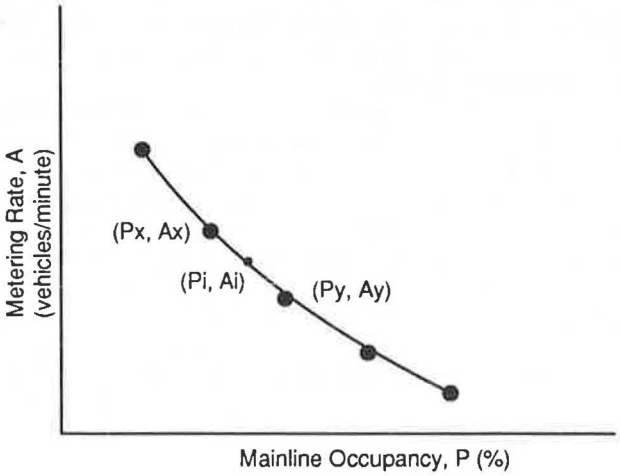

FIGURE 3 Occupancy-metering rate curve.

where

A_i = metering rate calculated,
A_x = metering rate associated with occupancy P_x (from the occupancy-metering rate curve),
A_y = metering rate associated with occupancy P_y (from the occupancy-metering rate curve),
P_i = mainline station occupancy at Station i, and
P_x and P_y = control points on the occupancy-metering rate curve.

The local metering rate calculation is not unique. Several systems around the country use this same occupancy control algorithm.

The System, or Bottleneck, Metering Rate

The unique aspect of this system is calculation of metering rates on the basis of system capacity constraints. The system,

or bottleneck, metering rate calculation is what makes the ramp control system an integrated traffic-responsive metering system.

As described in the handbook, integrated ramp control is distinguished by the application of "ramp control to a series of entrance ramps where the interdependency of entrance ramp operations is taken into account" (*2*). System-wide conditions and capacity constraints drive the calculation of metering rates at all metered ramps in the system.

The handbook describes integrated traffic-responsive metering as "the application of traffic-responsive metering to a series of entrance ramps where the metering rates are selected in accordance with system, as well as local, demand-capacity constraints" (*2*). Volume, occupancy, and/or speed measurements, taken in real time, define demand-capacity conditions for each mainline data collection location in the system. The handbook states that the calculations of both an independent and an integrated metering rate are based on these conditions. The more restrictive of the two is selected as the metering rate to be implemented. The metering rate selected is then subject to adjustment on the basis of ramp queues, maximum red times (minimum metering rate), and, potentially, other conditions.

The WSDOT algorithm is basically structured in the same manner. The independent metering rate calculation is the same as the local metering rate calculation described above. The adjustments to the selected metering rate are described below. The integrated metering rate calculation will be described in this section as the system, or bottleneck, metering rate calculation.

The WSDOT bottleneck metering calculation differs from the calculation method described in the handbook. The handbook describes the integrated metering rate calculation as a linear programming problem. It implies that the linear programming model is run off-line to determine the metering rates to be implemented for the range of traffic conditions to be expected. The precalculated metering rates are then selected in real time according to systemwide conditions.

However, the WSDOT bottleneck algorithm calculates metering rates in real time. In essence, it determines demand-capacity relationships in real time by a straightforward, simplistic approach to calculating capacity on-line. The demand-capacity relationships are then used to determine metering rates throughout the facility being metered.

The capacity of a freeway section is calculated in real time by determining whether the section is near capacity, based on occupancy, and whether vehicles are being stored in the section. A freeway section is defined by two adjacent mainline detector stations. The detector stations consist of a 6-ft by 6-ft induction loop detector in each of the freeway main lanes. In the Seattle control areas, mainline detector stations are located at a maximum of approximately ½-mi spacings. If the downstream detector station detects occupancies above an operator-defined threshold (generally in the neighborhood of 18 percent), the section is said to be operating near capacity. If the section is operating near capacity and the total volume entering the section exceeds the total volume exiting the section, then the section is said to be storing vehicles. The total volume entering the section consists of the volume across the upstream station, the volume on any entrance ramps in the section, the volume from any HOV facilities within the section, and the volume from any other roadway (collector-distributor or center reversible roadway) within the section. The total volume exiting the section consists of the volume across the downstream station, the volume on any exit ramps in the section, the volume going to any HOV facilities within the section, or the volume going to any other roadway within the section. In a generalized freeway section, such as the one depicted in Figure 4, these conditions can be described as follows:

1. Capacity condition

$$P_{it} \geq P_{\mathrm{THRESH}_i} \qquad (2)$$

where

P_{it} = average occupancy across the downstream detector over the previous 1-min period, and

P_{THRESH_i} = the occupancy threshold for the downstream detector station that defines when section i is operating near capacity. (These thresholds are parameters that can be tuned from the operator's console for each freeway section.)

2. Vehicle storage condition

$$q_{\mathrm{IN}_{it}} + q_{\mathrm{ON}_{it}} \geq q_{\mathrm{OUT}_{it}} + q_{\mathrm{OFF}_{it}} \qquad (3)$$

where

$q_{\mathrm{IN}_{it}}$ = volume entering section i across the upstream detector station during the past minute,

$q_{\mathrm{ON}_{it}}$ = volume entering section i during the past minute from the entrance ramp,

$q_{\mathrm{OUT}_{it}}$ = volume exiting section i across the downstream detector station during the past minute, and

$q_{\mathrm{OFF}_{it}}$ = volume exiting section i during the past minute on the exit ramp.

If these two conditions are met, the system calculates the upstream ramp volume reduction as the number of vehicles

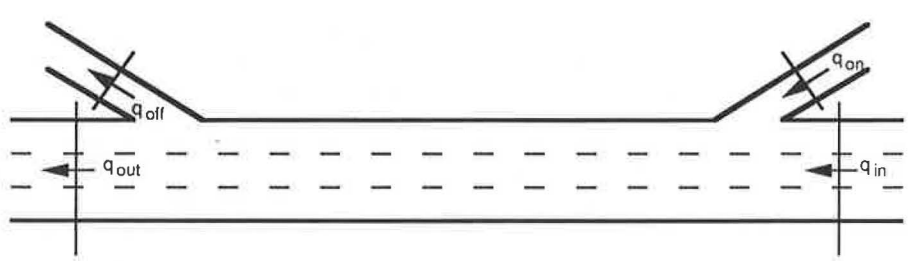

FIGURE 4 Generalized freeway section.

being stored in the freeway section during the past minute. This value becomes the total by which upstream ramp volumes must be reduced. The upstream ramp volume reduction is calculated as

$$U_{i(t+1)} = (q_{\mathrm{IN}_{it}} + q_{\mathrm{ON}_{it}}) - (q_{\mathrm{OUT}_{it}} + q_{\mathrm{OFF}_{it}}) \quad (4)$$

where $U_{i(t+1)}$ = upstream ramp volume reduction for section i to be acted on in the next metering interval $(t+1)$, and $q_{\mathrm{IN}_{it}}$, $q_{\mathrm{ON}_{it}}$, $q_{\mathrm{OUT}_{it}}$, and $q_{\mathrm{OFF}_{it}}$ are as stated for Equation 3 above.

Each freeway section has an area of influence assigned to it. Only upstream ramps within the section's area of influence are included in the volume reduction. The area of influence is defined by a tunable parameter that contains the number of upstream ramps that are affected by the bottleneck metering rate calculation for the given section. The parameters can be modified from the operator's console.

The total upstream ramp volume reduction is distributed to the upstream ramps on the basis of a set of weighting factors. Each metered ramp in the system is assigned a weighting factor according to how far downstream it is (how near it is to the bottleneck section) and the normal level of demand on the ramp. Ramps farther downstream (nearer the bottleneck) have larger weighting factors because vehicles using these ramps are most likely to pass through the bottleneck and reductions in metering rates nearer the bottleneck can have the quickest, most dramatic effect on the bottleneck. Ramps with higher demand tend to have higher volumes; therefore, ramps with higher demand can have a larger volume reduction in real terms.

The algorithm calculates the bottleneck metering rate reduction for each ramp within a given freeway section's area of influence by multiplying the total upstream ramp volume reduction by the given ramp's weighting factor, divided by the sum of the weighting factors for all the ramps within the section's area of influence. The calculation becomes

$$BMRR_{ji(t+1)} = U_{i(t+1)} \times \frac{WF_j}{\sum_j^n (WF_j)_i} \quad (5)$$

where

$BMRR_{ji(t+1)}$ = bottleneck metering rate reduction for ramp j based on section i for the next metering interval,

$U_{i(t+1)}$ = upstream ramp volume reduction for section i to be acted on in the next metering interval $(t+1)$,

WF_j = weighting factor for ramp j, and

$\sum_j^n (WF_j)_i$ = summation of weighting factors for all ramps within the area of influence for section i.

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

$$BMR_{ji(t+1)} = q_{\mathrm{ON}_{jt}} - BMRR_{ji(t+1)} \quad (6)$$

where

$BMR_{ji(t+1)}$ = bottleneck metering rate for ramp j based on section i for the next metering interval,

$q_{\mathrm{ON}_{jt}}$ = entrance volume on ramp j during the past minute, and

$BMRR_{ji(t+1)}$ = bottleneck metering rate reduction for ramp j based on section i for the next metering interval.

The system begins these calculations at the upstream end of the control area and works its way downstream for each section within the control area. Areas of influence for each freeway section overlap; therefore, any given ramp may have several bottleneck metering rates calculated for it. The most restrictive of these rates is selected as the final bottleneck metering rate for the ramp. (See Figure 5 for the flow diagram for the bottleneck metering calculation.)

Adjustments to the Calculated Metering Rate

As mentioned above, after both the local metering rate and the final bottleneck metering rate are calculated for a given ramp, the system selects the more restrictive of the two to be adjusted according to ramp conditions and subject to the maximum and minimum metering rates assigned to the ramp. There are a queue adjustment, a ramp volume adjustment, and an advance queue override.

The queue adjustment is implemented when the ramp queue has extended to the queue detector for a specified length of time. The queue detector is located upstream of the stop bar on the ramp, usually close to the intersection with the surface street and the ramp. When the occupancy level at the queue detector has exceeded a threshold value for a given length of time, the metering rate is increased by a small amount, usually one to three vehicles per minute, depending on the ramp and the length of time the queue condition has been in effect. The queue adjustment is essentially as described in the handbook.

The metering rates are calculated in real time to optimize the flow on the freeway. When the volume on the ramp differs from the assigned metering rate, either too many vehicles enter the freeway, which leads to breakdown conditions, or too few vehicles enter the freeway, which reduces the efficiency of freeway operations and exacerbates the ramp queuing problem. The system automatically adjusts the metering rate based on whether more or fewer vehicles entered the freeway at the ramp compared to the actual metering rate over the previous minute. If more vehicles entered than were supposed to, either due to violations or HOVs entering on the HOV bypass, the metering rate is reduced by the number of vehicles that entered in excess of the assigned metering rate. If fewer vehicles entered than were supposed to, usually due to inattention or inexperience on the part of the drivers, the metering rate is increased by the corresponding amount.

The final adjustment is the advance queue override. At selected ramps, a queue detector is located at the point of worst tolerable queue. If the ramp queue reaches this detector, then the metering rate is set relatively high. Depending on the ramp, this rate is in the range of 10 to 15 vehicles per minute. When the queue has cleared the advance queue detector, normal metering operation ensues. The reason for the override is one of equity. When the queue reaches the point

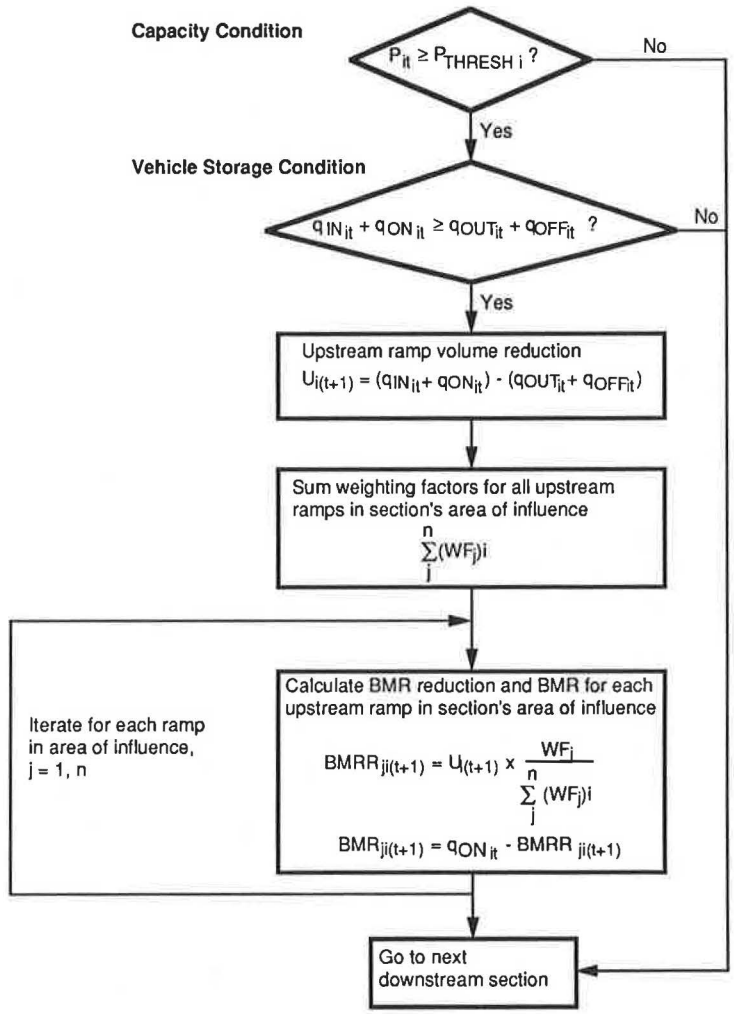

FIGURE 5 Bottleneck metering rate calculation flow diagram.

of worst tolerable queue, the system is starting to interfere with surface street operation and is affecting motorists not destined for the freeway. This is an undesirable situation, both politically and in terms of overall road network efficiency.

After all adjustment calculations are undertaken, the final metering rates are transmitted to the microprocessor-based controllers in the field for implementation. The entire algorithm is performed for all ramps and all freeway sections in all control areas every 20 sec, based on volumes and occupancies collected over the previous 1-min period.

Limitations of the Algorithm

There are some limitations apparent in the algorithm.

1. The bottleneck metering rate calculation does not include any estimation of origin-destination data. Therefore, the reduction of upstream ramp volumes calculated and then distributed over the bottleneck section's area of influence may meter vehicles off the freeway that are not destined for the bottleneck. Metering rates may be too restrictive under those conditions. However, the proper selection of areas of influence and weighting factors minimizes this problem. In the current system, there are no major exits from the system inside a given area of influence.

2. Because the bottleneck metering rate is calculated only when vehicles are being stored in a freeway section, a minor problem already exists in the section when the bottleneck calculation is put into effect. There also is a lag, equal to the travel time from the various upstream ramps to the bottleneck section, between the time the problem is detected and the time the actions taken can have a positive effect. Under severe circumstances, the system cannot catch up until the height of the peak is over. Under other circumstances, the system reduces ramp volumes significantly, severe queues form as the freeway clears, and then the advance queue override dumps traffic onto the freeway. Freeway conditions deteriorate as the queue clears and the system again reduces ramp volumes significantly while the queues build. This cycle tends to be dampened, and the system usually reaches equilibrium. (See "Future Direction," below, on ways to reduce these problems.)

3. The algorithm is very dependent on accurate volume information from the detectors in the field. In some areas of the country with severe weather conditions this may be a significant limitation. However, in the Seattle area, temper-

atures in both winter and summer are relatively mild and our experience with valid detector information in our control areas has been very good.

Advantages of the Algorithm

Despite these limitations, the metering system has been very successful. The advantages of the system are many.

1. The algorithm is well suited to real-time control. The calculations are very simple, but rely on many pieces of data and must be iterated many times quickly. These characteristics make it particularly suited to implementation in real time on minicomputers.
2. The system does not rely on origin-destination data. Although, as mentioned above, this may be viewed as a weak point theoretically, in practice, accurate origin-destination data are some of the most difficult and expensive data to gather. Origins and destinations change over time and from day to day. Having an effective system that does not require this information is advantageous.
3. Control strategies and metering plans do not have to be updated. Capacities do not have to be calculated off line. Therefore, the system requires little effort to keep operating effectively and there is no concern about metering plans aging.
4. The system automatically adjusts for incidents and weather conditions. When an incident occurs, the system operates under the same algorithm but reacts to the reduced capacity caused by the incident. The same situation applies when any condition, such as weather, reduces the operational capacity of the system.
5. Relatively few parameters need to be monitored. Only three parameters per ramp or freeway section need to be calibrated for the bottleneck algorithm—the number of upstream ramps in a section's area of influence, the occupancy threshold for a section to determine if it is operating near capacity, and the weighting factors for each metered ramp. These parameters rarely need to be modified. The minimum and maximum metering rates and the queue adjustment parameters are modified more often. Operators of the system modify these parameters as they are monitoring the system to respond to specific circumstances in the field. All parameters can be modified from the operator's console.

EVALUATION OF THE SYSTEM—METHODOLOGY AND RESULTS

To determine the effectiveness of the ramp control system, an evaluation has been ongoing since the system began operating (*3,4*). The performance of the corridor control system has been evaluated against its overall goal of more efficient movement of traffic within the corridor.

The principle of on-ramp control is to limit the number of vehicles entering the freeway so that the demand on the freeway does not exceed its capacity. The ramp meter should help maintain a stable flow in the freeway lanes. A stable flow minimizes congestion and its consequential shock waves, stop-and-go operation, and resultant loss in service.

Ramp metering has been an effective method of improving freeway operations in the Seattle metropolitan area. Ramp metering temporarily stores vehicles on the ramps to smooth out small peaks in freeway flows. The 22 meters on I-5 cause an average of less than 2 min delay per vehicle using the metered ramps during metering operation. The system has distributed demand among ramps in the system and discouraged short trips. In addition, the meters have encouraged the use of underutilized ramps and arterials.

Between 1981 and 1987, mainline peak period volumes increased about 86 percent northbound and 62 percent southbound. Violation rates at the ramp meters are low, ranging from 0.8 percent to 6.8 percent.

Ramp Delays

Delay is a critical performance measure for any traffic control system. For this evaluation, delay was defined as the difference between free-flow travel time and restricted-flow travel time. Delay was measured by comparing the time a car was in queue to its free-flow travel time from the beginning of the queue to the stop bar. The difference in these two measures was the delay. The Seattle metering system ramp delay study was conducted from April 14 to April 23, 1987.

The average delay at metered ramps was less than 2 minutes per vehicle during the morning and afternoon peak periods. During a one-half-hour period in the morning peak, average delays of 3.2 to 7.4 min occurred on 3 of the 13 ramps. The same ramps produced 5- to 8-min delays when measured in September 1983. Although these ramps produced up to 15-min delays during the first 6 months of operation, modifications in metering parameters and traffic patterns have subsequently reduced delays.

Signal Violations

Each violation of a ramp meter signal is registered by the ramp controller and transmitted to the central computer. The violation rate was found to vary from 0.8 to 6.8 percent for all ramps during 1986. Most violations occurred as the metering signal was first turned on and commuters were adjusting from free-flowing to metered conditions. Violations tended to diminish once a queue was formed.

Mainline Volumes

Mainline traffic volumes were calculated from the average volumes of detector stations spaced along I-5 during the months of September and October 1981 and March and October from 1982 to 1987. The results of the data analysis for the study section during the peak periods from September 1981 through March 1987 showed an 86 percent increase in volumes on northbound I-5 and a 62 percent increase in volumes on southbound I-5 (Table 1).

Not all of the reported volume increase can be attributed to the ramp metering system alone. There has been substantial growth in the urban, suburban, and exurban areas north of downtown Seattle since metering began, creating a much greater demand on I-5. In 1983, concurrent HOV lanes were added to both directions of I-5 in the metered corridor. The accident rate has decreased in the section since metering began. All of these factors have contributed to the increase in peak-period volumes on I-5. However, the contribution of metering to the volume increase cannot be overstated.

Mainline Travel Times

Travel time runs have been made over the years to determine whether any changes have occurred. Each run started at 7:30 a.m., the middle of the peak. Before metering was implemented, it took about 22 min to drive a specific 6.9-mile course from Lynnwood, a suburb of Seattle, to north Seattle. During the first 2 yr of metering, the travel times averaged between 12 and 13 min. In 1984, travel times for the year averaged 11.5 min. No travel time runs were made in 1985; and in 1986, they were made only in June, July, October, November, and December. The average of these travel times was 12.5 min. The only study conducted in 1987 was in September, and the average was 9.5 min (Table 2).

After metering was implemented, travel times showed an immediate and dramatic improvement. Since metering began, the travel times have remained fairly stable although mainline volumes during the morning peak have increased 49 percent. In other words, the mainline travel times have improved while traffic demands in the region have increased.

As with the increased mainline volumes, the improved travel times cannot be wholly attributed to metering. The initial travel time improvement was due primarily to metering. However, the addition of the HOV lanes and the reduced accident rates have contributed to maintaining the stable travel times.

Accident Data

Accident data were gathered for all accidents in the 12.4-mile section of I-5 (from 44th Avenue West to the Ship Canal Bridge, excluding the express lanes). The accident study was conducted during the period from October 1, 1976, to May 31, 1987. Data, matching peak-period flows, were collected on southbound I-5 between 6:00 a.m. and 9:00 a.m. and on northbound I-5 between 3:30 p.m. and 6:30 p.m.

From the premetering period (October 1976 through September 1981) to the latest evaluation period (March 1985 through May 1987), the northbound accident rate during the afternoon peak period dropped from 1.49 to 0.92 accidents per million vehicle-miles, a 38 percent decrease. The average northbound volume during the afternoon metering period increased 86 percent.

Southbound accident rates were lower than northbound rates. One possible reason for this is that southbound traffic consists mostly of commuters who are familiar with the system. Also, northbound traffic in the afternoon is a mix of many types of trips, including noncommuter trips, and the traffic volume on northbound I-5 is higher than that southbound, thereby increasing the drivers' chance of conflicts.

The southbound accident rate during the morning peak period dropped from 1.31 to 0.79, a 40 percent decrease, from the premetering period to the latest evaluation period. The average southbound volume during the morning metering period increased 62 percent. In Table 3, the northbound accident rates during the afternoon peak and the southbound accident rates during the morning peak are shown.

Relative Accident Rates

A comparison of accident experience on I-5 under ramp metering was made with a similar section of I-5 not under ramp control. The comparison section was a portion of I-5 south of downtown Seattle. Accident rates from March 1985 through May 1987 were compared to the 5-yr period just before the implementation of the metering system (1976–1981). The accident rates (accidents per million vehicle-miles of travel) were for the peak direction during peak hours.

For the afternoon peak, the accident rate in the ramp control section declined from 1.49 accidents per million vehicle-miles to 0.92 accidents per million vehicle-miles although there was virtually no change in the comparison section, which had 1.1 accidents per million vehicle miles during both periods (Figure 6).

For the morning peak, both the comparison section and the ramp control section showed a drop in accident rates. However, the ramp control sections showed considerably greater decline in accident rates, from 1.31 accidents per million vehicle-miles to 0.79 accidents per million vehicle-miles, than the comparison section, where accidents declined from 1.1 per

TABLE 1 PEAK PERIOD MAINLINE VOLUME

	Average Mainline Volumes	
Year	SB I-5 6:00 - 9:00 a.m.	NB I-5 3:30 - 6:30 p.m.
Sept. 81	10,685	11,491
81-82	11,550	12,330
82-83	12,210	15,413
83-85	13,038	17,673
85-87	17,267	21,332

TABLE 3 ACCIDENT RATES DURING PEAK PERIODS

	Accident rate per million vehicle miles traveled (MVMT)	
Study Period	NB I-5 3:30 - 6:30 p.m.	SB I-5 6:00 - 9:00 a.m.
10/1/76 - 9/29/81	1.49	1.31
9/30/81 - 3/31/82	1.10	0.93
4/1/82 - 8/28/83	1.08	0.92
8/29/83 - 2/28/85	1.15	1.44
3/1/85 - 5/31/87	0.92	0.79

TABLE 2 SOUTHBOUND TRAVEL TIMES (7:30 a.m.)

	Travel Times (minutes)					
Section Length (miles)	Sept. 1981	Oct. 1981 - Sept. 1982	Oct. 1982 - Sept. 1983	1984	1986	Sept. 1987
6.9	22.8	12.4	13.0	11.5	12.5	9.5

million vehicle-miles to 0.9 per million vehicle-miles (Figure 7).

Not all the reduction in accident rates can be attributed to the metering system. However, the accident rates during the peak periods in the peak direction in the ramp control section of I-5 decreased more than in the comparison section of I-5 south of downtown Seattle. Although there may be other factors contributing to the accident rate reduction, it appears that the metering system is a significant cause of the reduced accident rates.

FUTURE DIRECTION

The future of the SC&DI system holds some significant changes. Two major programs currently in progress will have major impacts on the system. The first is the reconstruction of I-90. This project will add 450 loops to the existing 900. It will also add 75 new CCTV cameras, 15 VMSs, 30 ramp meters, and 25 data accumulators. These additions to the system do not include 90 miles of SC&DI systems to be added on other area freeways. The existing computer system does not have the capacity to accommodate these additions. As a result, the I-90 reconstruction project will involve replacing the existing TSMC central control system, including both hardware and software.

New software is being redesigned in a modular format to allow as much flexibility as possible. The new software will provide a "slot" in the decision tree to allow easy implementation of any new algorithm. A new algorithm will be tested on-line and the new software will be capable of easily activating or deactivating this slot in the decision tree. This feature will allow the software to be debugged and adjusted without significant programming changes. This same software philosophy will be used throughout the new system, allowing for easy implementation and experimentation with other types of algorithms such as incident detection.

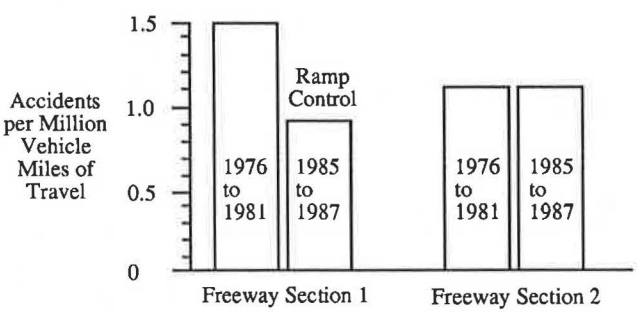

FIGURE 6 Relative accident rates—afternoon peak period.

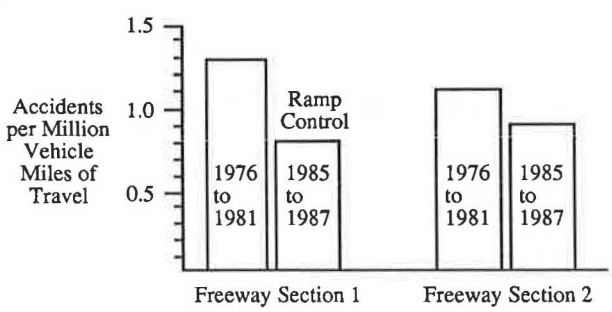

FIGURE 7 Relative accident rates—morning peak period.

In addition to the hardware and software upgrade described above, work is under way as part of the WSDOT's Freeway and Arterial Management Effort (FAME) research program to investigate ways to improve the existing metering algorithm. Researchers hope that by employing a predictive algorithm, they can overcome the time lag limitation mentioned above. By predicting traffic conditions 1 to 2 min in the future, the system could better anticipate conditions and reach an equilibrium state more quickly and smoothly.

Another modification to be investigated is the performance of the advance queue override check before any other metering rates for the ramps are calculated. Any ramps in the advance queue override will not undergo any other metering rate calculations and will be flagged to be dropped from consideration in the bottleneck metering rate calculation. This modification will allow the entire upstream ramp volume reduction to be distributed over only those ramps whose metering rates can be reduced, making the system more responsive to actual traffic conditions.

The TSMC redesign and the FAME project are not directly related. However, both programs are progressing with the goals of the other program in mind so that they can be easily integrated into a single final product.

SUMMARY

The existing real-time ramp-metering system in the Seattle area uses an integrated traffic-responsive metering algorithm. The algorithm is simple in its approach but very effective in its application. The system has proven to be effective in a series of ongoing evaluations.

WSDOT is expanding the system and upgrading hardware and software. Research efforts are under way to improve the efficiency of the algorithm employed.

The software for the new computer system will be structured to allow incorporation of newly developed metering algorithms. As new algorithms are developed, this new system will easily be able to use them and test their effectiveness. This system will prove to be a very valuable tool in the overall, nationwide effort to develop advanced freeway management systems.

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