Stratified Zone Metering-The Minnesota Algorithm

Minnesota Experience

For over thirty years, the Minnesota Department of Transportation (Mn/DOT) has used freeway ramp metering to ease the merge of traffic from entrance ramps onto the mainline and to reduce freeway congestion in the Twin Cities metropolitan area. In late 2000, the effectiveness of ramp metering was studied extensively by an independent consultant by analyzing freeway traffic with and without ramp meters. Following the study, it was concluded that ramp metering is beneficial for increasing freeway volume, decreasing freeway travel times, increasing freeway speeds, and decreasing crashes. At the time of the study, public opinion surveys were also conducted, and, although the majority of those surveyed agreed that ramp meters did improve driving conditions, the majority also thought that wait times at meters were excessive. After the ramp meter evaluation results were released, Mn/DOT decided that although the current metering algorithm did help to ease mainline congestion, it did not completely comply with the concerns of the public. An unrestrictive set rate that did not factor in real-time changes in traffic flow was then set for all meters. In late 2001, a new metering strategy was developed by Mn/DOT and is now being implemented on many Twin Cities highways.

Real Time Data Sampling

The goal of Stratified Zone Metering is to ease freeway congestion while limiting meter wait times. This is done by releasing vehicles onto the freeway based on ramp demand so that freeways are safer, travel times are more reliable, and ramp wait times are not excessive[1].

In order for meters to be "sensitive" to current traffic conditions, it is imperative that constant changes in traffic patterns affect the rates in which meters run. Consequently, loop detectors (traffic sensors in the pavement) send volume and speed data to the Traffic Management Center (TMC). The volumes (number of vehicles) for all detectors are compiled every thirty seconds. The thirty-second volumes are converted to approximate hourly volumes by means of a smoothing function (see Appendix; Smoothing Function), and these hourly volumes are the volumes used in the algorithm.

Demand

On each entrance ramp that is metered, there is a queue detector and a passage detector. The queue detector on a ramp is placed at the top of the ramp and is used to approximate the number of vehicles entering the ramp. Thirty-second volumes from queue detectors are converted to hourly volumes, as explained above, and these volumes generate the demand at the meters. In the case of a malfunctioning or non-existent queue detector, the passage detector (placed immediately after metering poles) will be used to get an approximation for the demand at that meter (see Appendix; Malfunctioning or Non-Existent Queue Detector).

Wait Time Regulation

The primary issue of public concern regarding metering has to do with long wait times on ramps. Consequently, one of the top priorities for the new algorithm is to ensure that the wait time on a metered ramp is less than approximately four minutes. In order to keep wait times below this threshold, a unique "minimum release rate" is applied to each metered ramp. A minimum release rate is designed so that even if vehicles are backed up to (but not over) the queue detector, the last vehicle on that ramp will not have to wait longer than four minutes. To

[1] The target wait time is <4 minutes. While it's understood that some motorists may experience waits of more than four minutes, the mean ramp wait time is four minutes or less.

calculate the minimum release rate, first, the number of vehicles (T) that can be stored on the ramp is estimated using average vehicle lengths, ramp density (how close together vehicles are in queue on the ramp), current release rates, and ramp dimensions (see Appendix; Ramp Density and Queue Storage). To assure that no vehicle waits over four minutes, four minutes is divided by the estimated maximum number of vehicles stored on the ramp to produce the maximum cycle time (C_{max}) for the meter.

$$C_{\max} = \frac{240(\text{seconds in four minutes})}{T}$$

Maximum cycle time can be converted to a minimum hourly release rate (R_{min}) by dividing one hour by the maximum cycle time.

$$R_{\min} = \frac{3600(\text{seconds in an hour})}{C_{\max}}$$

No meter cycle time can be greater than fifteen seconds; therefore, 240 vehicles per hour is the absolute minimum release rate for any meter. It is helpful to remember that cycle times and wait times have an inverse relationship-a longer cycle time corresponds with a lower hourly release rate.

If a queue detector reads an occupancy level (percentage of time detector senses vehicle) of over twenty-five percent, it is assumed that the queue is backed up near or over the queue detector. When this occurs, the demand for that meter is incrementally increased until the queue detector is no longer covered. Also, as a safeguard, the minimum release rate is set to the demand at the meter. By raising the minimum release rate to the ramp demand, the queue will shrink and ramp wait times will remain acceptable. As explained later, a higher demand rate for a meter will cause a faster cycle time and a higher release rate. The demand is increased appropriately (by 150 vehicles per hour every thirty seconds) so that the meter will reach the maximum release rate (2.1-second cycle time; 1714 vehicles per hour) within four minutes.

Metering Zones

Detector stations are pairs or groups of detectors on the mainline spaced approximately every half-mile. Using stratified zone metering, detector stations from a half-mile to three miles apart are used as endpoints to individual metering zones. Within each zone, the ambition of stratified zone metering is to keep the number of vehicles entering a zone less than the number leaving. There are three variables by which vehicles can enter a zone (Inputs) and three by which they may leave (Outputs).

Inputs:	
(M)	Metered Entrances: Entrance ramps onto any given freeway that are metered.
(A)	Upstream Mainline Volume: Total number of vehicles entering a zone through the station at the beginning of the zone. (See Appendix; HOV and Auxiliary Lanes)
(U)	Unmetered Entrances: Entrance ramps onto any given freeway that are not metered.

Outputs:	
(X)	Exits: all exit ramps off any given freeway.
(B)	Downstream Mainline Volume: Total number of vehicles leaving a zone through the station at the end of the zone. Regardless of actual station volume, the value for the B station is set to the approximate capacity of that station: Right lane 1800, all other lanes 2100 veh/hr. A (B) station value based on anything other than capacity would often result in an unreasonable volume. (See Appendix; HOV and Auxiliary Lanes)
(S)	Spare Capacity: If a zone is free-flowing with little traffic, there is said to be "spare capacity" on the mainline, and meters will not need to be as restrictive. For this reason, the spare capacity is regarded as an output. This variable is calculated using average freeway densities for free-flowing traffic compared to current freeway densities (see Appendix; Spare Capacity).

Layers

Due to the fact that detector stations are spaced only a half-mile apart and zones range from a half-mile to three miles in length, zones within the freeway system overlap. This overlap of zones causes there to be "layers" of zones. The first layer contains all zones consisting of exactly two stations (usually about 1/2 mile in length). The second layer has all zones with three stations (1 mile in length). There are six layers total that follow this pattern (See Table 1). For clarification, the zones may be labeled (Zone 1-2). Zone 1-2, for example, would be in layer one, two zones from the furthest upstream. This concept of layers is necessary for stratified zone metering to be effective. In order to further understand layers, see page 9 or Layers.pdf for an example of layers on a segment of freeway.

Table 1: Layers and Zone Lengths

Layer	Stations	Length
1	2	0.5 miles
2	3	1 mile
3	4	1.5 miles
4	5	2 miles
5	6	2.5 miles
6	7	3 miles

The Algorithm

As mentioned earlier, the objective of stratified zone metering is to regulate zones through metering so that the total volume exiting a zone exceeds the volume entering. For this to happen, the relationship of inputs and outputs within a given zone is as follows:

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

Therefore,

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

Through this calculation, M is the maximum number of vehicles allowed to pass through all meters in any given zone between stations A and B. The key to stratified zone metering is to disperse the volume M throughout the zone suitably depending on demand (D) on the metered entrance ramps. D is the total number of vehicles that need to enter a freeway through all metered entrances within a given zone. In order to disperse M appropriately, calculations are made one zone at a time from upstream to downstream (beginning with Zone 1-1) as follows:

$$R_n = \frac{M * D_n}{D}$$

R_n is the proposed rate for meter n (n is a meter within the zone).
D_n is the demand for the meter n.

Therefore, based on demand, this calculation gives a proposed rate for every meter to run in according to a percentage of M. This calculation begins with Zone 1-1 in the first layer. After R_n has been calculated for the first layer, the proposed rates for all meters are compared to the demand and minimum rates for each corresponding meter.

For all meters where the proposed rate is less than the minimum release rate (discussed earlier), the proposed rate is set to the minimum release rate. The meters that have a proposed rate greater than the demand and the meters that have proposed rate less than the minimum release rate need to have their proposed rates recalculated. These, therefore, have their proposed rates recalculated upstream to downstream using the second layer (beginning with Zone 2-1). The same process is involved for the second layer as the first. However, those meters that have been set to the minimum release rate are “locked in” at that minimum release rate, and this is also factored into the calculation of the zones in the second layer. This process will continue one layer at a time until all proposed rates are less than (or equal to) demand but greater than (or equal to) the minimum rates.

After all proposed rates for meters have been established, the zones that were involved with calculating the final proposed rates must be inspected. If the sum of release rates in one of these zones is less than M for that zone, this is a “broken zone” and needs to be corrected. If not corrected, meters in this zone would be more restrictive than necessary. If a broken zone is found, the meters that have proposed rates controlled by that zone are temporarily set to the maximum release rate. These meters alone are processed again beginning in the first layer as they were before. This will correct the problems of the broken zones and the proposed rates will all be finalized and implemented for the next thirty-second period. See page 5 for numeric examples of the algorithm process.

Various zones may be disqualified from being used in some cases. If any detector in the upstream mainline volume station (A) malfunctions, the zone is disqualified. See appendix (Fake Detectors) for information on exit and unmetered entrance ramp detection that has failed. Also, if there is a drop in density greater than fifty vehicles per mile from one mainline detector to the next downstream detector in the same lane, the zone is disqualified. This scenario suggests that there is an incident on the roadway or heavy congestion and stratified zone metering is inappropriate. If this scenario occurs, each meter in that zone is set to its “simple plan” rate which is 130% of its expected maximum hourly volume.

Operation Times

Each freeway corridor has an assigned time in which meters are allowed to run. During this time, yet even before the meters begin to run, the algorithm is used to determine what the release rates at the meters should be. When demand on a given ramp is greater than eighty percent of its calculated release rate, the meter will turn on.

Example of Stratified Zone Metering

The following pages contain examples that are based on TH 169 NB from Valley View Rd up to 36th Street. The zones and layers used in the examples are the zones on the table found on page 9. However, the data used for volumes are fictitious. These examples are simplified and do not take into account smoothing functions that filter incoming data. These examples do not give a perfect representation of the calculation processes of the algorithm, but they do represent how ramp demand factors into setting release rates and how layers of zones are used.

Example 1:

Calculate all vehicles allowed to pass through meters in a given zone (M).

Calculate M for Zone 1-4.
Data from Table 2 represents real time, thirty-second data that has been converted to hourly volumes.

Table 2: Example Volumes

Location	Volume
TH 62 Station (A)	1700
EB 62 Meter (Demand)	1000
EB 62 HOV Bypass (U)	50
WB 62 Exit (X)	150
WB 62 Meter (Demand)	900
Exit to Bren Rd. (X)	300
Bren Rd. Station (B)	2700*

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

$$M \leq 2900 + 450 + 0 - 1700 - 50$$

$$M \leq 1600 \text{ vehicles per hour}$$

This calculation for M is repeated for all zones in all layers.

*At Bren Rd, there are two lanes; thus, the B station value is 1800 + 2100 = 2900.

Example 2:

Table 3 data represents the demand and minimum release rates for each metered ramp.

Table 3: Demand and Minimum Rates of Metered Ramps

Meter	Current Demand	Minimum Rate
Valley View Rd.	500	300
TH 62 EB	1000	500
TH 62 WB	900	600

Bren Rd.	700	400
Lincoln Dr.	400	300
Excelsior Blvd.	800	500
TH 7	700	700
36th St.	300	200

The following data represents the zones that are metered, ramp(s) metered in that zone, and calculated M values.

Table 4: M Values for Metered Zones

Zone	Metered Ramp(s)	M Value
1-2	Valley View Rd.	400
1-4	TH 62 EB, TH 62	1400
1-5	Bren Rd.	800
1-6	Lincoln Dr.	600
1-7	Excelsior Blvd.	700
1-9	TH 7	600
1-10	36th St.	400
2-1	Valley View Rd.	500
2-2	Valley View Rd.	550
2-3	TH 62 EB, TH 62 WB	1750
2-4	TH 62 EB, TH 62 WB	1900
2-5	Bren Rd., Lincoln Dr.	1300
2-6	Lincoln Dr., Excelsior Blvd	1250
2-7	Excelsior Blvd.	900
2-8	TH 7	550
2-9	TH 7, 36th St.	950
3-1	Valley View Rd.	525
3-2	Valley View Rd., TH 62 EB, TH 62 WB	2000
3-3	TH 62 EB, TH 62 WB, Bren Rd.	2000
3-4	TH 62 EB, TH 62 WB, Bren Rd., Lincoln Dr.	2400
3-5	Bren Rd., Lincoln Dr., Excelsior Blvd.	1300
3-6	Lincoln Dr., Excelsior Blvd.	1300
3-7	Excelsior Blvd., TH 7	1200
3-8	TH 7, 36th St.	1000

Using the calculated M values, proposed rates (R_n) for the above meters can be determined.

$$R_n = \frac{M * D_n}{D}$$

So, for the EB 62 Ramp in Zone 1-4,

$$R_n = \frac{1400 * 1000}{1900} = 737$$

M is found in Table 4, D_n is found in Table 3, and D = 1000 + 1900 (sum of demand for EB and WB 62).

The following are the proposed rate values for each meter after checking the first layer of zones. Also, the proposed rates that are too high or too low are noted.

Valley View Rd	400	
62 EB	736	
62 WB	663	
Bren Road	800	This rate is greater than demand.
Lincoln Dr.	600	This rate is greater than demand.
Excelsior Blvd	700	
TH 7	600	This rate is less than minimum release rate and needs to be raised.
36th St.	400	This rate is greater than demand.

Keeping these problems in mind, the proposed rates are recalculated (where necessary) using the second layer of zones. Notice that zone 2-4 is the first zone of layer two that will be used for calculation because the first proposed rate with a problem is Bren Rd.

Proposed rate calculations are continued one layer at a time until all meters' proposed rates fall between the minimum release rate and the demand for that meter.
The following are the results of the proposed rates and the zone that was used to come up with the proposed rates. The zone used is needed to look for "broken zones" so meters are not more restrictive than necessary.

Table 5: Proposed Rates

Meter	Proposed Rates	Zone Used in Calculation
Valley View Rd.	400	1-2
TH 62 EB	730	2-4
TH 62 WB	658	2-4
Bren Rd.	466	3-5
Lincoln Dr.	300	3-5

Excelsior Blvd.	500	3-7
TH 7	700	1-9
36th St.	250	2-9

The zones listed in Table 5 are analyzed and zones 3-5 and 2-4 are found to be “broken zones” because M values are less than the total proposed rates in these zones.

Zone 3-5: M = 1300 (see Table 4) Total proposed rate: 466 + 300 + 500 = 1266
Zone 2-4: M = 1900 (see Table 4) Total proposed rate: 730 + 658 + 466 = 1854

The meters effected by these zones are processed again in the same manner as before and this process results in the final meter rates (See Table 6).

Table 6: Final Meter Rates

Meter	Rate (Veh. Per Hour)	Zone Used for Calculation
Valley View Rd.	400	1-2
TH 62 EB	736	1-4
TH 62 WB	664	1-4
Bren Rd.	492	3-5
Lincoln Dr.	308	3-5
Excelsior Blvd.	500	3-7
TH 7	700	1-9
36th St.	250	2-9

Table 7: Stratified Zone Metering Example (Hwy 169 NB)

Location	Layer 1										Layer 2									Layer 3								Layer 4							Layer 5						Layer 6				
76th St	A										A									A								A							A						A				
Exit ...	X										X									X								X							X						X				
Valley View Rd	B	A									S	A								S	A							S	A						S	A					S	A			
... Meter		M									M	M								M	M							M	M						M	M					M	M			
69th St		B	A								B	S	A							S	S	A						S	S	A					S	S	A				S	S	A		
EB Exit ...			X									X	X							X	X	X						X	X	X					X	X	X				X	X	X		
T.H.62			B	A								B	S	A						B	S	S	A					S	S	S	A				S	S	S	A			S	S	S	A	
... EB Meter				M									M	M							M	M	M					M	M	M	M				M	M	M	M			M	M	M	M	
... HOV Bypass				U									U	U							U	U	U					U	U	U	U				U	U	U	U			U	U	U	U	
... WB Exit				X									X	X							X	X	X					X	X	X	X				X	X	X	X			X	X	X	X	
... WB Meter				M									M	M							M	M	M					M	M	M	M				M	M	M	M			M	M	M	M	
Exit ...				X									X	X							X	X	X					X	X	X	X				X	X	X	X			X	X	X	X	
Bren Rd				B	A								B	S	A						B	S	S	A				B	S	S	S	A			S	S	S	S	A		S	S	S	S	A
... Meter					M									M	M							M	M	M					M	M	M	M			M	M	M	M	M		M	M	M	M	M
... HOV Bypass					U									U	U							U	U	U					U	U	U	U			U	U	U	U	U		U	U	U	U	U
Exit ...					X									X	X							X	X	X					X	X	X	X			X	X	X	X	X		X	X	X	X	X
Lincoln Dr					B	A								B	S	A						B	S	S	A				B	S	S	S	A		B	S	S	S	S	A	S	S	S	S	S
... Meter						M									M	M							M	M	M					M	M	M	M			M	M	M	M	M	M	M	M	M	M
Exit ...						X									X	X							X	X	X					X	X	X	X			X	X	X	X	X	X	X	X	X	X
Excelsior Blvd						B	A								B	S	A						B	S	S	A				B	S	S	S	A		B	S	S	S	S	B	S	S	S	S
... Meter							M									M	M							M	M	M					M	M	M	M			M	M	M	M		M	M	M	M
... HOV Bypass							U									U	U							U	U	U					U	U	U	U			U	U	U	U		U	U	U	U
Exit to T.H.7							X									X	X							X	X	X					X	X	X	X			X	X	X	X		X	X	X	X
Van Buren Way							B	A								B	S	A						B	S	S	A				B	S	S	S			B	S	S	S		B	S	S	S
T.H.7								B	A								B	S	A						B	S	S					B	S	S				B	S	S			B	S	S
... Meter									M									M	M							M	M						M	M					M	M				M	M
36th St									B	A								B	S							B	S						B	S					B	S				B	S
... Meter										M									M								M							M						M					M
Exit ...										X									X								X							X						X					X
Minnetonka Blvd										B									B								B							B						B					B

Appendix:

Smoothing Function:
V: Volume Samples (Collected every 30 seconds from loop detectors)
G: Hourly flow rate
F_t: Smoothed flow for time t
K: Constant used to determine the rate of smoothing
Therefore,

$$G = V * 120 \text{ (samples per hour)}$$

And,

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

Some K values:
Flow Rate for Any Loop Detector: K = 0.15
Current Release Rate: K = 0.27
Fake Detector (see below) Flow Rate: K = 0.01

Malfunctioning or Non-existent Queue Detector:
In the case of a malfunctioning or non-existent Queue Detector, the Passage detector is used to estimate the "passage demand" at the ramp. The passage detector can only count the vehicles that have passed the metering poles; therefore, to be assured of an acceptable queue, 10% is added to the smoothed passage volume to calculate passage demand. Also, the minimum release rate can never drop below the passage demand value.

$$D_t = D_{t-1} + K * (1.1 * P_t - D_{t-1})$$

D_t = Passage Demand at Time t.
K = Smoothing Constant (0.15)
P_t = Passage Detector Flow Rate.

Ramp Density and Queue Storage:
N: Queue Density
R^a: Accumulated Release Rate (see below)
T: Number of Storable Vehicles
8: length from metering pole to queue detector (feet)
p: number of metering poles (lanes formed in queue)
L = (**8** – 100) * p (It is assumed that when vehicles back up within 100 feet of the queue detector, they are already slowing down over the queue detector)

$$N = -0.03445 * R^a + 206.715 \text{ **}$$

And,

$$T = \frac{N * L}{5280 \text{(feet per mile)}} = \frac{(-0.03445R + 206.715)L}{5280}$$

**Based on an observation and analysis study of vehicle behavior on metered entrance ramps. See Queue Density Research Results for further explanation.

Accumulated Release Rate:
K = .27 for Accumulated Release Rate; thus,

$$R^a_t = R^a_{t-1} + K * (R_t - R^a_{t-1})$$

R^a_t: Accumulated Release Rate at time t.

Spare Capacity:
The amount of spare capacity within any given zone is estimated using the following steps:

1. Density (vehicles/mile) is calculated for each mainline detector within the zone (not including Auxiliary, HOV, or CD lanes).
2. The detector with the greatest density (D_{max}) is compared to 32 vehicles per mile. If $D_{max} \geq 32$ veh/mi, Spare Capacity for the zone is 0. Otherwise "Spare Density" (D_{spare}) is calculated.

$$D_{spare} = 32 - D_{max}$$

3. The spare density is converted into a rate of flow (S_{lane}) as follows:

$$S_{lane} = D_{spare}({}^{veh}/_{mi}) * speed({}^{mi}/_{hr}) = S_{lane}({}^{veh}/_{hr})$$

   speed = speed at the detector with D_{max}.

4. This Spare Capacity per lane is multiplied by the number of lanes (n) in the B station at the end of the zone to get the Spare Capacity of the zone; thus,

$$S = S_{lane} * n$$

In Summary,

If $D_{max} \geq 32$,

$$S = 0;$$

Else,

$$S = (32 - D_{\max}) * speed * n$$

Fake Detectors:
Exit ramps, unmetered entrances, auxiliary lanes, and HOV lanes are critical areas that need detection for the algorithm to be effective. If a detector in one of these areas fails, a "Fake Detector" is used to approximate volume. A unique fake detector has been assigned to each detector (of the types listed above), and this fake detector gives an approximation for the detector volume. This approximation is made based on a sum, difference, or percentage of surrounding detectors or is given a constant value.

For example, detector 37 is an exit detector. If it fails,
Detector 37 = 153 percent of Detector 49 minus Detector 38; that is,

$$37 = (49 - 38) * 1.53.$$

HOV and Auxiliary Lanes:
If an HOV or Auxiliary Lane is included in an A or B station that is used in any given zone, vehicles counted in these lanes cannot be counted in the station volume. Volumes are expected to be lower for Auxiliary and HOV lanes; thus, they would have an adverse effect on A and B station values.

If in an A station, HOV and Auxiliary lanes are included in the Unmetered Entrance totals (U).

If in a B station, HOV and Auxiliary lanes are included in the Exit totals (X).