be warranted at locations where the geometrics are substandard and the primary concern is to improve the safety of the merging operation.

Integrated Ramp Control

Integrated ramp control refers to the application of ramp control to a series of entrance ramps where the interdependency of entrance ramp operations is taken into account. The primary objective of integrated ramp control is to prevent or reduce the occurrence of congestion on the freeway. Therefore, the control of each ramp in the control system is based on the demand-capacity considerations for the whole system rather than on the demand-capacity constraint at each individual ramp. This concept does not necessarily imply the use of large computer control systems since small subsystems may be coordinated by the use of mutual coordination of adjacent ramp meter controllers.

If congestion is to be prevented or reduced on the freeway system, the concept of integrated ramp control must be used in the design of a system of controls for a section of freeway with more than one entrance ramp. It is applied in the following types of systems:

- Integrated pretimed metering (including ramp closure)
- Traffic-responsive metering
- Gap-acceptance merge control

A discussion of integrated ramp control applied to each of these systems follows.

Integrated Pretimed Metering. Integrated pretimed metering refers to the application of pretimed metering to a series of entrance ramps. The metering rate for each of these ramps is determined in accordance with demand-capacity constraints at the other ramps as well as its own local demand-capacity constraint. These metering rates, which are computed from historical data pertaining to each control interval, require the following information:

- Mainline and entrance ramp demands
- Freeway capacities immediately downstream of each entrance ramp
- Description of the traffic pattern within the freeway section to be controlled

This information provides the basis for establishing the demand-capacity constraints of the entrance ramps and their interdependencies.

- Fundamental metering rate calculations — Given the required data, the fundamental procedure for computing metering rates involves five steps:

(1) Start with the entrance ramp which is farthest upstream.

(2) Determine the total demand (upstream mainline demand plus ramp demand) for the freeway section immediately downstream of the ramp.

(3) Compare the total demand to the capacity of the downstream section, and proceed as follows:

  (a) If the total demand is less than the capacity, metering is not required at this ramp by this demand-capacity constraint. Therefore, skip Step 4 and go immediately to Step 5.

  (b) If the total demand is greater than the capacity, metering is required at this ramp by the demand-capacity constraint. Therefore, proceed to Step ~~5~~ 4.

(4) Compare the upstream mainline demand to the capacity of the downsteam section, and proceed as follows:

  (a) If the upstream mainline demand is less than the capacity, then the allowable entrance ramp volume (or metering rate) is set equal to the difference between the capacity and the upstream mainline demand.

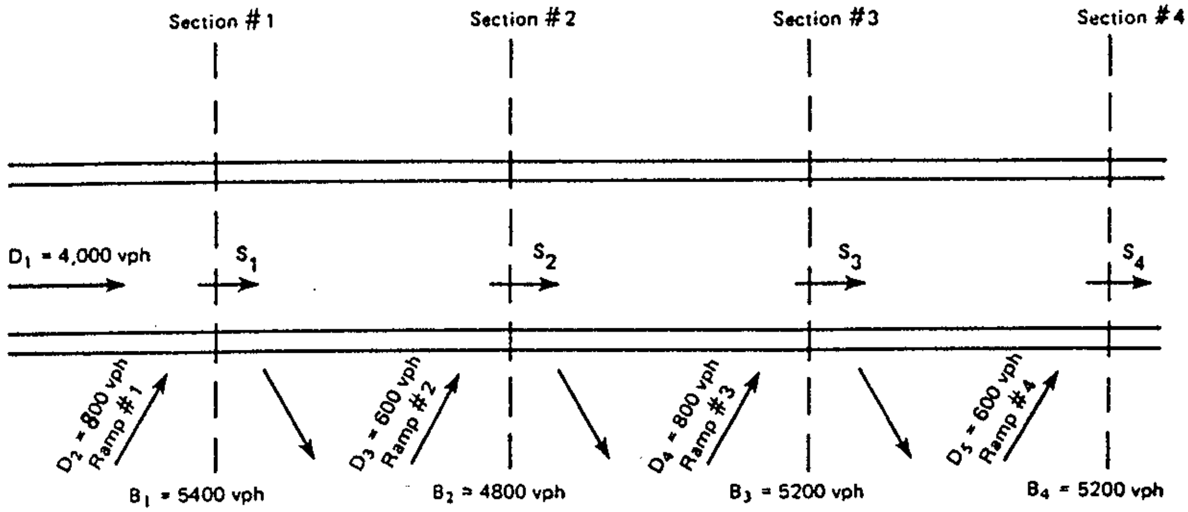
  (b) If the upstream mainline demand is greater than or equal to the capacity, then the allowable entrance ramp volume is zero, and the ramp must be closed. If the upstream mainline demand is greater than the capacity, the volumes permitted to enter at ramps upstream must be reduced accordingly.

  The total reduction in the allowable entrance ramp volumes upstream is equal to the difference between the upstream mainline demand and the capacity, adjusted to account for that portion of the traffic entering upstream that exits before it reaches the downstream entrance ramp being closed.

(5) Select the next entrance ramp downstream, and go back to Step 2.

This procedure is illustrated by the following examples.

- Example No. 1 — In the example case shown in Figure 4.14, pretimed metering rates are calculated for



X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = 4000$ vph
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4000)+(1.00)(800) = 4800 \text{ vph} < B_1 = 5400 \text{ vph}; \therefore X_2 = 800 \text{ vph}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4000)+(0.75)(800)+(1.00)(600) = 5000 \text{ vph} > B_2 = 4800 \text{ vph}; \therefore X_3 = 400 \text{ vph}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4000)+(0.70)(800)+(0.90)(400) + (1.00)(800) = 5320 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore X_4 = 680 \text{ vph}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4000) + (0.60)(800) + (0.85)(400) + (0.90)(680) + (1.00)(600) = 5432 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore X_5 = 368 \text{ vph}$

Conclusion:

- Ramp #1: No control needed.
- Ramp #2: Meter at a rate of 400 vph.
- Ramp #3: Meter at a rate of 680 vph.
- Ramp #4: Meter at a rate of 368 vph.

Figure 4.14. Integrated entrance ramp control: Example No. 1 — Calculation of pretimed metering rates

an integrated, pretimed control system comprised of four entrance ramps. In a review of this example, the following points should be noted:

- Since only entrance ramp control is being considered and not mainline control, the allowable mainline volume at Section 1, X_1 is set equal to the mainline demand D_1.
- With the notation given in Figure 4.14, the demand, S_j, at a Section, j, is computed by the following equation:

$$S_j = \left(\sum_{i=1}^{j} A_{ij}X_i \right) + A_{j+1,\,j}D_{j+1} \qquad (4.1)$$

Where:

X_i = Allowable volume at Input i
D_i = Demand at Input i
A_{ij} = Decimal fraction of vehicles entering at Input i which pass through Section j
S_j = Demand at Section j

As it happens, the metering rate computed for each entrance ramp in this particular example is determined solely by the demand-capacity constraint at the section immediately downstream and is not influenced by the demand-capacity constraints at other ramps.

- Example No. 2 — The data given in the example shown in Figure 4.15 are the same as that given in the previous example, except that the mainline demand, D_1, is 4,600 vph instead of 4,000 vph. In this case, the metering rates at Ramps 2, 3, and 4 are determined solely by their respective downstream demand-capacity constraints, as was the case in the previous example. However, the metering rate at Ramp 1, rather than being determined by the demand-capacity constraint at Section 1, is established in accordance with the demand-capacity constraint at Ramp 2, as is described below.

The demand, S_2, at Section 2 is 5,570 vph, which is 770 vph greater than the capacity, B_2, at Section 2 (4,800 vph). If Ramp 2 is closed, the demand at Section 2 is reduced to 4,970 vph, a volume which also exceeds the capacity, B_2. Therefore, it is necessary to reduce the allowable volume, X_2, entering at Ramp 1 (Input 2). The allowable volume, X_2, must be reduced enough to reduce the demand, S_2, by 170 vph. The amount of the reduction is equal to the 170 vph divided by the decimal fraction, A_{22}, of the vehicles entering at Ramp 1 and passing through Section 2 (170 vph/0.75 = 227 vph). Therefore, the allowable volume, X_2, at Ramp 1 would be 573 vph instead of 800 vph.

In this procedure, excess demand, $S_j - B_j$, at any section, j, is removed by reducing the allowable volume on the entrance ramp immediately upstream. If, instead, the allowable volumes on entrance ramp farther upstream were reduced, a large number of vehicles would have to be removed from these ramps in order to reduce the demand, S_j, sufficiently at any section, j. This is necessary because some of the vehicles that enter at these ramps will exit the freeway before they reach Section j.

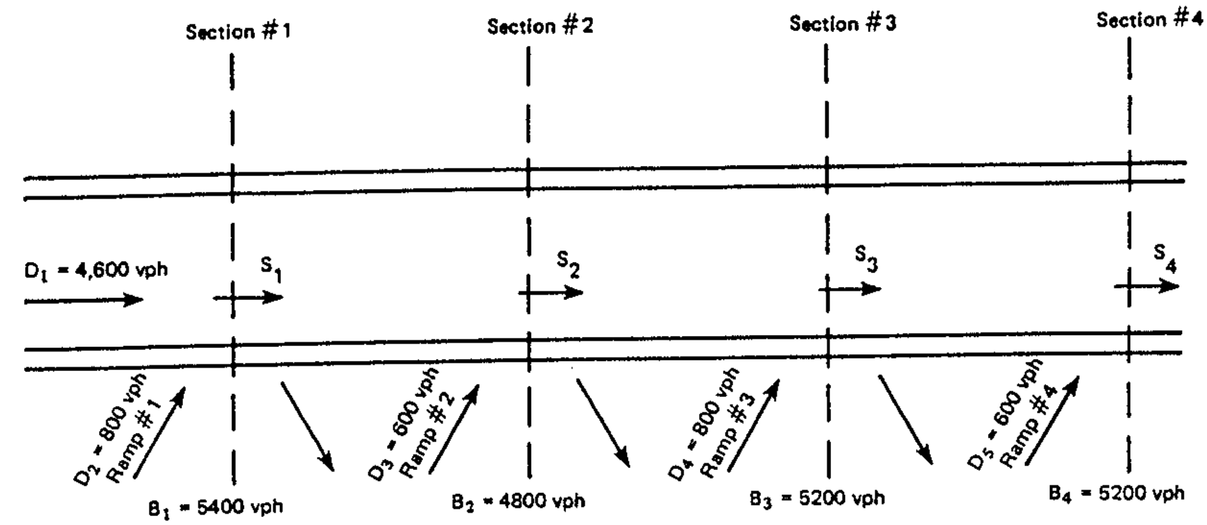
- Example No. 3 — Again, in the situation presented in Figure 4.14, allowable ramp volumes would be calculated as follows. If the excess demand (200 vph) at Section 2 were to be removed by reducing the allowable volume, X_2, at Ramp 1, the volume at Ramp 1 would have to be reduced by 267 vph. Consequently, the allowable entrance ramp volumes would be as follows:

Ramp No.		Volume (vph)
Ramp	1	533
Ramp	2	600
Ramp	3	687
Ramp	4	352
Total input		2,172

The total input of 2,172 vph, however, is less than that of 2,248 vph, the volume which is obtained if Ramp 2 is metered as in Example 1. Thus, the fundamental approach described will result in the optimal utilization of the freeway. It maximizes the sum of the allowable entrance ramp volumes, a procedure which corresponds to maximizing system output for steady-state, noncongested flow conditions (*35*). The total travel in the system is also maximized (*36*).

Linear Programming Formulation — The fundamental procedure described in Examples 1 and 2 can be formulated as a linear programming model (*35*). This model may be used to compute optimal allowable entrance ramp volumes. In terms of the notation defined in Figures 4.14 and 4.15, the linear programming model would be as follows:

- Maximize ΣX_i, where n is the number of inputs
- Subject to the following constraints:
  - Demand capacity:



X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1$ = 4600 vph
- $S_1 = A_{11}X_1 + A_{21}D_2$ = (1.00)(4600)+(1.00)(800) = 5400 vph = B_1 = 5400 vph; $\therefore X_2$ = 800 vph
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3$ = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 vph > B_2 = 4800 vph;

  $\therefore X_3$ = 0 and volume entering upstream must be reduced by 170 vph;
  $\therefore X_2$ = 800 – 170/A_{22} = 800 - 170/0.75 = 573 vph

  4970 600 770 reduce 170 $A_{22} \cdot X_2 = 600$ $X_2 = 573$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4$ = (0.90)(4600)+(0.70)(573)+(0.90)(0) + (1.00)(800) = 5341 vph > B_3 = 5200 vph; $\therefore X_4$ = 659 vph
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5$ = (0.85)(4600) +(0.60)(573) +(0.85)(0) + (0.90)(659) + (1.00)(600) = 5447 vph > B_4 = 5200 vph; $\therefore X_5$ = 353 vph

Conclusion:

- Ramp #1: Meter at a rate of 573 vph.
- Ramp #2: Close.
- Ramp #3: Meter at a rate of 659 vph.
- Ramp #4: Meter at a rate of 353 vph.

Figure 4.15. Integrated entrance ramp control: Example No. 2 — Calculation of pretimed metering rates

$$\sum_{i=1}^{n} A_{ij}X_i \leq B_j; \quad j = 1,..., n-1 \qquad (4.2)$$

- At Section 1, allowable mainline volume ≤ mainline demand:

$$X_1 = D_1 \qquad (4.3)$$

- Allowable entrance ramp volume ≥entrance ramp demand:

$$X_i \leq D_i; \ i = 2,....,n \qquad (4.4)$$

- Allowable entrance ramp volume equals minimum allowable ramp volume:

$$X_i \geq \min x_i \geq 0; \ i = 2,....,n \qquad (4.5)$$

The use of the linear programming model yields allowable entrance ramp volumes which are identical to those obtained by using the fundamental procedure described above.

Practical Considerations — The allowable entrance ramp volumes (or metering rates) calculated for an integrated ramp control system should be evaluated with respect to the following practical considerations:

- Metering rates of less than 180 to 240 vph (3 to 4 vpm) are not feasible because drivers required to wait longer than 15 to 20 sec at a ramp metering signal often believe that the signal is not working correctly. They will, therefore, proceed on a red indication by the signal. Thus, if a metering rate of less than 180 to 240 vph is calculated, consideration should be given either to closing the ramp or to metering it at a higher rate.
- Practical maximum metering rates are about 900 vph for single-entry metering and approximately 1,100 vph for platoon metering. Therefore, for a metering rate greater than the maximum for the metering type to be used, it should be set less than or equal to the practical maximum rate, and the metering rates at the other entrance ramps should be adjusted accordingly.
- Metering rates at each entrance ramp should be evaluated with regard to available storage at the ramp and potential resulting congestion on the adjoining surface street system. If the storage is not sufficient, it may be necessary either to close the ramp or to increase the metering rate.
- Metering rates equal to zero indicate that an entrance ramp closure is necessary. However, the closure of a particular entrance ramp may not be acceptable. Therefore, it may be necessary to increase a zero metering rate to some minimum acceptable rate.
- The procedure described for computing metering rates gives preference to traffic entering the system near the upstream end. Consequently, metering rates at entrance ramps downstream may be too restrictive to be acceptable to the motoring public. Therefore, it may be necessary to increase the metering rates computed for some of the downstream entrance ramps, and thus to reduce accordingly the metering rates for some of the upstream entrance ramps.

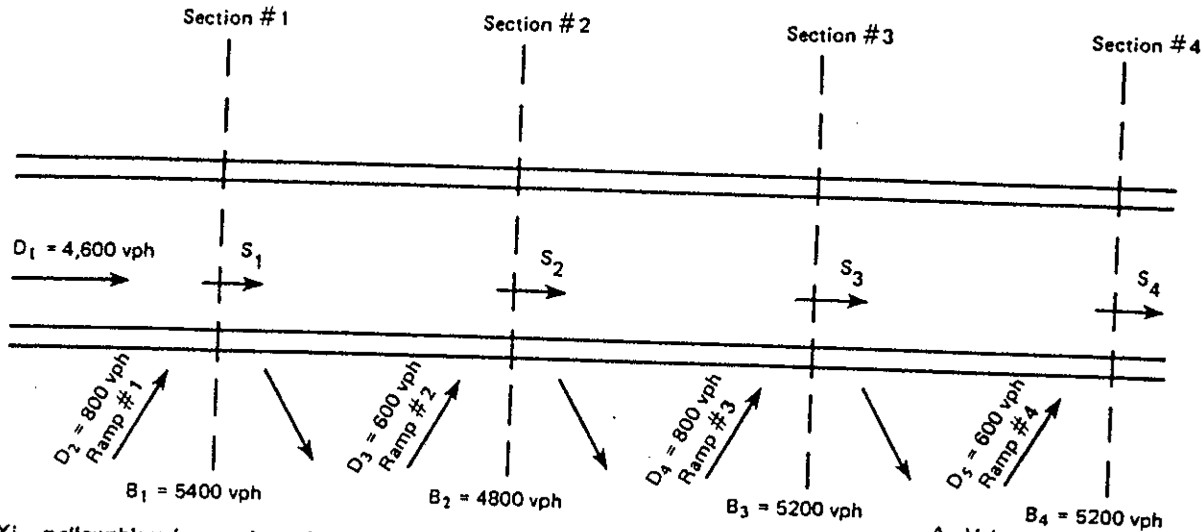
If any of the computed metering rates were to be altered because of one or more of the practical considerations mentioned above, the metering rates at the other entrance ramps would have to be adjusted accordingly to ensure both an optimal utilization of the freeway and a noncongested flow.

- Example No. 4 — If it were necessary to maintain a metering rate of at least 240 vph at Ramp 2 in the example presented in Figure 4.15, it would be necessary to follow the adjustment procedure for the metering rates at the other entrance ramps (as shown in Figure 4.16). The allowable volume, X_2 (573 vph), at Ramp 1 would have to be reduced by 320 vph in order to allow 240 vph to enter at Ramp 2 and still satisfy the demand-capacity constraint at Section 2. This reduction also decreases the mainline demand at Sections 3 and 4. Thus, the allowable volumes at Ramps 3 and 4 are increased to maximize the utilization of the freeway at these sections.

It is usually difficult to obtain reliable estimates of the A_{ij} values, because these vary with time and generally exhibit a high variance. Also, the O/D type studies used to collect these data are expensive and do not provide real-time data.

Integrated Traffic-Responsive Metering. Integrated traffic-responsive metering is the application of traffic-responsive metering to a series of entrance ramps where the metering rates at each ramp are selected in accordance with system, as well as local, demand-capacity constraints.

- System operation — During each control interval, real-time measurements are taken of traffic variables (usually volume, occupancy, and/or speed). The data are used to define the demand-capacity conditions at



X_j = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = \underline{4600 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4600)+(1.00)(800) = 5400 \text{ vph} = B_1 = 5400 \text{ vph}; \therefore X_2 = \underline{800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 \text{ vph} > B_2 = 4800 \text{ vph};$

  Since X_3 must equal at least 240 vph; $X_3 = 240$ vph and volume entering upstream must be reduced by 410 vph;
  $\therefore X_2 = 800 - 410/A_{22} = 800 - 410/0.75 = \underline{253 \text{ vph}}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4600)+(0.70)(253)+(0.90)(240) + (1.00)(800) = 5333 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 667 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4600) + (0.60)(253) + (0.85)(240) + (0.90)(667) + (1.00)(600) = 5466 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 334 \text{ vph}}$

Conclusion:

- Ramp #1: Meter at a rate of 253 vph.
- Ramp #2: Meter at a rate of 240 vph.
- Ramp #3: Meter at a rate of 667 vph.
- Ramp #4: Meter at a rate of 334 vph.

Figure 4.16. Integrated entrance ramp control: Example No. 4 — Calculation of pretimed metering rates

each entrance ramp. Then, on the basis of these measurements, both an independent and an integrated metering rate are calculated for each entrance ramp. Of these two metering rates, the one that is the more restrictive is selected to be used during the next successive control interval.

- Metering rates — The methods used to calculate independent and integrated traffic-responsive metering rates are basically the same as those used to compute independent and integrated, pretimed metering rates. Usually, instead of metering rates being calculated in real time, a set is precomputed for the range of demand-capacity conditions expected, from which the metering rates are then selected in real time. The linear programming model is often used to calculate predetermined sets of integrated, traffic-responsive metering rates. Also, the metering rates are usually subject to the merge-detector, queue-detector, and maximum-red-time overrides used in traffic-responsive metering.

Integrated Gap-Acceptance Merge Control. Integrated, gap-acceptance merge control is the application of gap-acceptance merge control to a series of entrance ramps where such control at the individual ramps is subject to system demand-capacity constraints.

Metering rates are computed by the procedure described for calculating integrated, pretimed metering rates. These integrated metering rates are computed for each entrance ramp on the basis of the real-time measurements of traffic variables which are used to define the system's demand-capacity conditions. Then, for each entrance ramp, a minimum acceptable gap setting is determined which will yield a ramp volume corresponding to the integrated metering rate. The minimum acceptable gap is the smallest gap in freeway mainlane traffic into which a ramp vehicle will merge. Larger settings of a minimum acceptable gap have the impact of reducing the metering rate.

Integrated vs. Independent Ramp Control. Comparisons of integrated and independent entrance ramp control indicate that increased benefits are realized with integrated ramp control (*37, 38*). Improvements occur in terms of the following:

- Lower travel time
- Higher total travel
- Fewer accidents

In addition, in the case of traffic-responsive metering, the greater system flexibility provided by integrated ramp control enables an optimal system response to individual variations in traffic demands and capacities resulting from incidents on the freeways.

Controller Interconnection. A significant feature of integrated ramp control is the interconnection among local ramp controllers which permits conditions at one location to affect the metering rate imposed at one or more other locations. Real-time metering plans are computed and updated by a central master controller, which issues metering rates to the respective local ramp controllers, based on freeway traffic information obtained from vehicle detectors throughout the system.

Figure 4.17 depicts a schematic representation of an integrated entrance ramp control system. The freeway is divided into sections, with each section containing one entrance ramp. Although the decision-making capabilities are centralized within the master controller, the processing of control intelligence may be distributed among the individual entrance ramps. For economic (and possibly reliability) reasons, there is a trend for decentralized decision-making, distributed computation, and hierarchical control (*39*).

A discussion of decentralized control of integrated ramp metering systems is provided by Loose, et al. (*39*).

Incremental Benefits of Different Levels of Control

As discussed earlier, the benefits offered by pretimed metering (including ramp closure) versus no access control include increased mainline speeds (reduced travel time), higher service volumes, less delay, safer merging operations, and reduced user costs. Beyond pretimed metering, the incremental benefits gained from traffic-responsive metering (local or systemwide) depend on the following factors (*40*):

- Variations in the ratio of mainline to entrance ramp demand — As mainline demand approaches capacity, the permissible metering rates become more and more constrained. On the other hand, as the mainline demand decreases, more traffic can be allowed onto the freeway from entrance ramps, and ramp metering control can exert greater impact on the quality of freeway flow, thus producing greater benefits.

  A measure of how much traffic-responsive control can vary the metering rates is called the controllability index, which is defined by the following formulation (*40*):

$$\text{Controllability Index} = \frac{I_{pc} - I_{min}}{I_{min}} \qquad (4.6)$$