Coordinating Ramp Meter Operation with Upstream Intersection Traffic Signal

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Freeway entrance ramp meters are commonly located immediately downstream of a signalized intersection. As a result of the cyclic operation of the intersection signal, traffic tends to enter the ramp in platoons; hence the ramp traffic arrival rate is nonuniform within each signal cycle. Conventionally, the metering rate is uniform over a period longer than a signal cycle. Hence, nonuniform arrival traffic onto the ramp may lead to insufficient use of ramp storage capacity and cause unnecessary delay to ramp traffic. The possibility of employing a two-level variable metering rate to reduce delay at a ramp meter signal is investigated. The problem is modeled as minimizing total ramp delay D with two variables: $M1$, the metering rate in the first level, and s, the switching point. It is pointed out that D is a convex function in $M1$ for fixed s, but not convex in s for fixed $M1$. An optimization method is proposed that will lead to the optimum $M1$ and s. The ramp capacity is kept unchanged. Example results indicate that ramp delay can be reduced by using the optimum metering rates and metering rate switching point.

In the past 30 years, freeway entrance ramp meters have been installed in the United States and elsewhere to regulate ramp traffic onto freeways and reduce congestion. A number of different ramp metering systems have been developed, ranging from the simplest local fixed-time operation to more advanced types such as an integrated traffic-responsive control system.

In most cases, especially in urban areas, ramp meters are located immediately downstream of a signalized intersection. As a result of the cyclic operation of the intersection signal, traffic tends to enter the ramp in platoons as each signal phase releases a stopped queue; hence the ramp traffic arrival rate is nonuniform within each signal cycle. Even though sophisticated ramp metering systems can adjust ramp metering rates on the basis of traffic conditions, metering rates are usually uniform over a period longer than a signal cycle. Therefore, in each cycle, nonuniform arrival traffic may lead to insufficient use of ramp storage capacity, since the ramp meter may be "starved" during the intervals between platoons and overloaded after the platoons arrive. Delay to ramp traffic may be unnecessarily greater than it should be. Delay may be reduced by varying the metering rate to adapt to the upstream intersection signal release pattern. For example, instead of being uniform, the metering rate could be increased when the platoon arrives and decreased after it is served without changing the number of vehicles that can be released onto the freeway in a cycle. However, to reduce potential disturbance to the freeway, ramp traffic as well as freeway traffic should be considered together in determining the higher metering rate.

So far only limited research on the coordination of ramp meter operation and upstream intersection traffic signals has been reported (*1,2*). In this paper the possibility of employing a variable metering rate to reduce the delay at a ramp meter signal is investigated. The example results indicate that ramp delay could be minimized by using the optimum metering rates and metering rate switching point.

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MODELING RAMP METER OPERATION

Figure 1 shows a typical freeway entrance ramp—intersection traffic signal configuration. Figure 2 shows a representative profile of ramp traffic arrivals. $T1$ represents the interval in which the service road receives the green signal (travel time from the intersection to the ramp is not considered in this analysis because the dynamics of the ramp traffic is the focal point rather than the platoon dispersion between the upstream traffic signal and the ramp meter) and through Movement 1 proceeds; a portion of this flow (Flow Rate $q1$) enters the ramp (the remainder continues along the service road). During $T2$, side street left-turn Movement 2 receives the green signal and a portion of this flow (Flow Rate $q2$) enters the ramp. $T3$ represents the interval in which a portion of side street right-turn Movement 3 proceeds to the ramp at a flow rate of $q3$. Usually a uniform metering rate M is used to regulate the ramp traffic. To make sure that the ramp queue clears after each cycle, M should satisfy the following condition:

$$M \cdot (T1 + T2 + T3) \geq q1 \cdot T1 + q2 \cdot T2 + q3 \cdot T3 \qquad (1)$$

The left-hand side of expression 1 is the maximum number of vehicles that can enter the freeway with the selected metering rate,

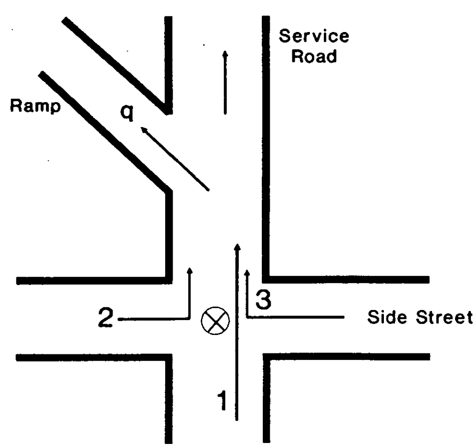

FIGURE 1 Typical freeway-intersection signal configuration.

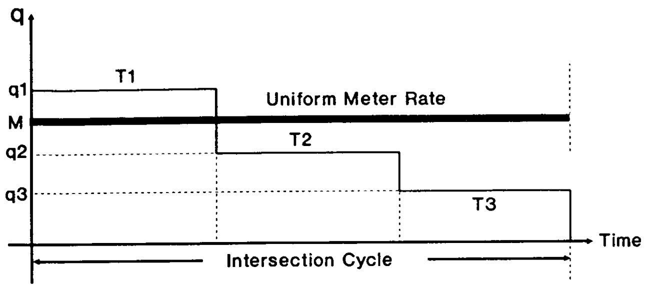

FIGURE 2 Ramp arrival rate.

M. Under this condition, the queue length should be 0 at the beginning of each cycle. On the other hand, M should be subject to the practical minimum and maximum metering rates, $M\text{min}$ and $M\text{max}$:

$$M\text{min} \le M \le M\text{max} \tag{2}$$

The metering rate M satisfying Conditions 1 and 2 represents a typical existing scenario.

The proposed technique is shown in Figure 3. Instead of a uniform metering rate M, $M1$ should be used for s sec before it is changed to $M2$ for the remaining part of the cycle. s is called the switching point and satisfies the following condition:

$$0 \le s \le T1 + T2 + T3 \tag{3}$$

To keep the same maximum number of vehicles that can enter the freeway, the following constraint is imposed:

$$M1 \cdot s + M2 \cdot (T1 + T2 + T3 - s) = (T1 + T2 + T3) \cdot M$$

$$M2 = [(T1 + T2 + T3)\, M - M1 \cdot s] \div (T1 + T2 + T3 - s) \tag{4}$$

Although there are unknown variables $M1$, $M2$, and s, $M2$ can be expressed as a function of $M1$ and s by Equation 4. Therefore, only two variables need to be specified: $M1$ and s. $M1$ should satisfy the following constraints:

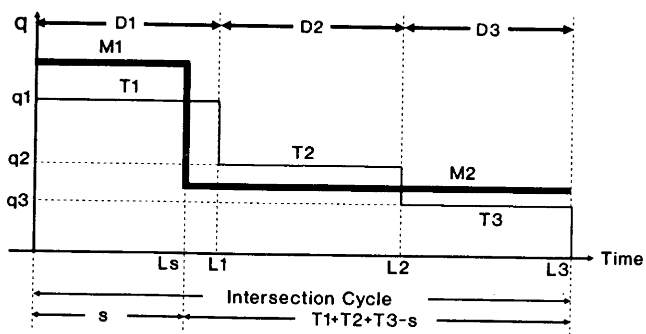

FIGURE 3 Variable metering rate.

$$M\text{min} \le M1 \le M\text{max}$$

$$M\text{min} \le M2 = [(T1 + T2 + T3)\, M - M1 \cdot s] \div (T1 + T2 + T3 - s) \le M\text{max} \tag{5}$$

The following notation is used:

Ls = ramp queue length at switching point s;
$L1$ = ramp queue length at time $T1$;
$L2$ = ramp queue length at time $T1 + T2$; and
$L3$ = ramp queue length at time $T1 + T2 + T3$.

The objective function is the total delay to ramp traffic, which can be expressed as

$$D = D(M1,s) = 1/2(D1 + D2 + D3) \tag{6}$$

where $D1$, $D2$, and $D3$ are the total delay to ramp traffic in intervals $T1$, $T2$, and $T3$, respectively.

Under this formulation, the problem has been modeled as a two-dimensional minimization problem:

Minimize $D(M1,s)$

subject to Constraints 3, 4, and 5, assuming that M is known and satisfies Constraints 1 and 2.

OPTIMIZATION METHOD

An investigation of the functional properties of $D(M1,s)$ indicates that although D is convex or quasi-convex in $M1$, it is not necessarily convex in s. However, since the switching point s should normally be an integer, there would be a limited number of possible choices for s. For example, if the cycle time is 120 sec (which is usually the maximum cycle length for most intersection signals), there would be only 121 points for s to be considered. Hence a direct search on s can be made to minimize D for a fixed $M1$, whereas a one-dimensional optimization method such as a golden section search, suitable for a convex or quasi-convex function, can be used for minimizing D for a fixed s. Hence the following minimization method can be employed to locate the optimum value of $M1$ and s where $D\text{min}$ is the current minimum value for D and $M1\text{min}$ and $s\text{min}$ are the current values for $M1$ and s that produce $D\text{min}$.

Step 1. Set $s = 0$, $s\text{min} = 0$, and set $D\text{min}$ to the maximum number that can be stored in the computer. Go to Step 2.
Step 2. For the given s, use the golden section search method to locate the local minimum D, subject to Constraint 5. If $D < D\text{min}$, the current values of $M1$ and s are used for $M1\text{min}$ and $s\text{min}$. Increase s by 1. Go to Step 3.
Step 3. If s is not greater than the cycle length ($T1 + T2 + T3$), go to Step 2. Otherwise stop, and the optimum solution point is at $M1\text{min}$ and $s\text{min}$.

SIMULATION TEST

To demonstrate the potential benefit of employing a variable metering rate, a simulation test was conducted using a simple Paradox for Windows program. For a time period T, if the initial queue length is $L0$ and the ramp volume and metering rate are q and M, respectively, the queue length at the end of T is simply given by

$$L_T = \begin{cases} L0 + (q - M) \cdot T & \text{if } L0 + (q - M) \cdot T > 0 \\ 0 & \text{otherwise} \end{cases}$$

The delay to the ramp traffic incurred during T is the area under the queue length curve.

The program uses the following parameters to calculate the queues and delays:

$T1$ = 50 sec	$T2$ = 30 sec	$T3$ = 40 sec
$q1$ = 800 vehicles/hr (vph)	$q2$ = 500 vph	$q3$ = 300 vph
Mmin = 300 vph	Mmax = 1,000 vph	M = 600 vph

Under the control of a uniform meter rate of 600 vph, the total ramp delay is 162.96 vehicle-sec, and the maximum ramp queue length is 2.78 vehicles.

Using the proposed technique, the total ramp delay can be minimized to 6.82 vehicle-sec (a 96.5 percent reduction) at s = 50 sec, $M1$ = 800 vph, with the maximum ramp queue length reduced to 0.36 vehicle (87 percent shorter). Also, $M2$ = 457 vph. As in the case of a uniform metering rate, the ramp queue clears at the end of the cycle.

Figure 4 shows the contour of total ramp delay D as a function of ramp meter rate $M1$ and switching point s. Figure 5 plots the evolution of the ramp queue length as a function of time within the intersection cycle.

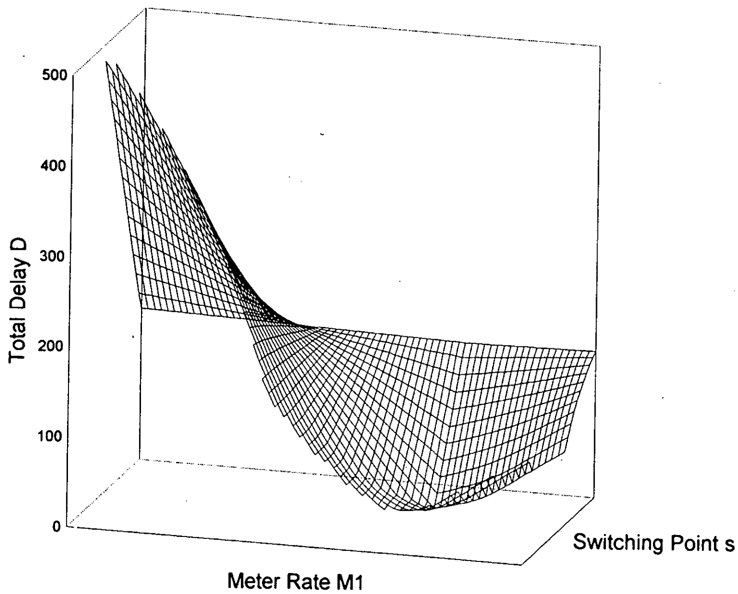

FIGURE 4 Ramp delay D as function of $M1$ and s.

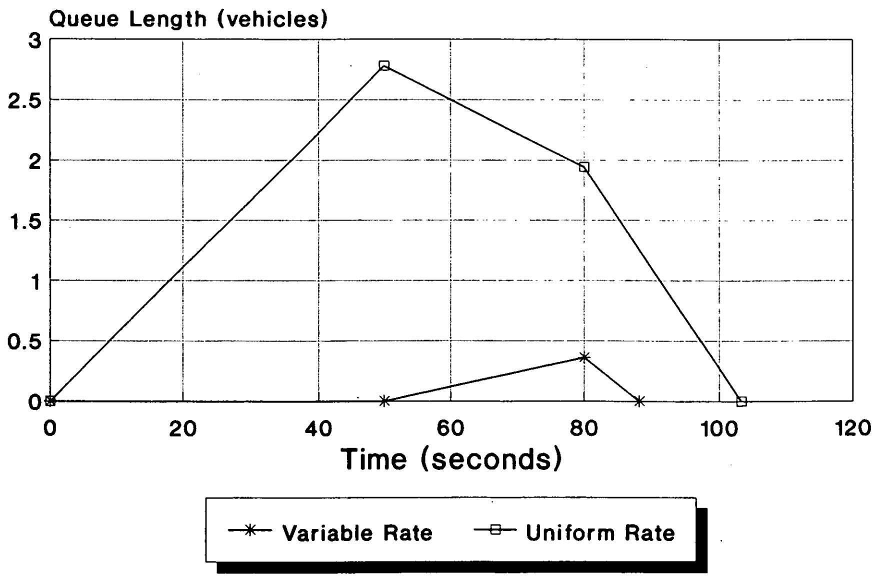

FIGURE 5 Evolution of ramp queue length.

DISCUSSION OF RESULTS

It can be seen from Figure 5 that under the control of a uniform metering rate, a queue forms in the first time period $T1$ when there are heavy vehicular arrivals; therefore more delay results afterward. The proposed technique, however, uses a metering rate equal to the arrival rate in $T1$ for the whole length of $T1$; therefore no ramp queue occurs during $T1$. Although the metering rate is reduced for $T2$ and $T3$, the ramp delay would not increase since the queue left at the end of $T1$ is 0 and the arrival rates in $T2$ and $T3$ are much lower. Also, the ramp queue clears sooner.

CONCLUSION

It can be seen from the simulation test that ramp delay and maximum ramp queue length can be reduced by applying a variable metering rate instead of a uniform one.

Because the ramp capacity remains the same in each cycle, the maximum number of vehicles released to the freeway remains constant; therefore, the disturbance of ramp traffic to freeway traffic caused by a variable metering rate should be small. To reduce this disturbance, the higher metering rate $M1$ should be determined by considering both the freeway traffic and the ramp volume. $M1$ should also be determined so that a minimum spacing between vehicles released by the ramp meter can be realized.

If ramp traffic is very heavy, the ramp has to operate at the maximum metering rate so that the queue does not spill back to the upstream intersection.

The proposed technique is a first step toward microscopically modeling the complicated freeway-arterial coordination problem. It has the potential to be extended and adapted for a real-time advanced traffic management system. Additional research is needed to further quantify the benefits, test the practicality of the approach via field measurements, and develop a technique for determining parameters of the arrival rate profile.

REFERENCES

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