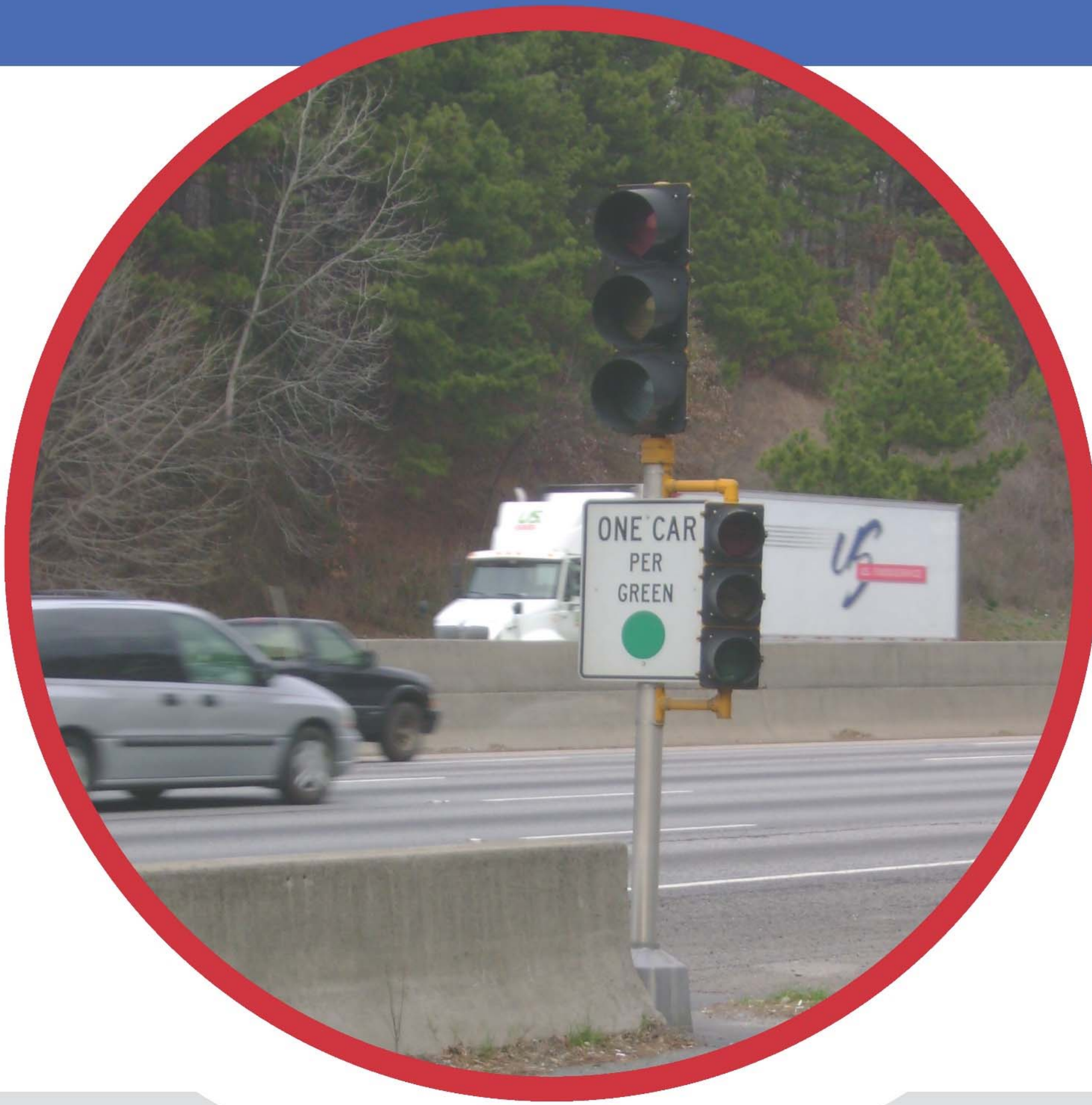
National Research



M-0468 Ramp Metering Feasibility Study for Cabarrus, Gaston, Iredell and Mecklenburg Counties

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Introduction

This report summarizes research conducted by Atkins on the state of ramp metering systems throughout the United States and abroad. The report was originally prepared for the *Ramp Metering Feasibility Study for Durham and Wake Counties* and has been updated for this project. It reviews ramp metering hardware, software/firmware, site selection criteria, implementation methods, and design standards currently used by agencies that employ ramp meters. This research includes the measures of effectiveness that ramp meters have provided to those agencies.

1. Ramp Meter Overview

This section includes a brief overview of ramp meters and a discussion of their components, benefits, and drawbacks.

1.1. Ramp Meter History

Ramp metering was first introduced in 1963 on Chicago's Eisenhower Expressway as a method to deal with safety issues caused by the newly constructed Interstate Highway program's increased freeway demand, speed, congestion, and the associated collisions. Other early adopters in the 1960s were Los Angeles and Detroit. Early ramp metering was accomplished by positioning a police officer at an entrance ramp to stop and release vehicles at a predetermined rate. These early applications proved successful in achieving smoother merging onto freeways and did not disrupt mainline flows. Ramp metering systems soon spread to other metropolitan areas, and the method of a police officer manually metering the ramp was replaced with various types of traffic signal and gate assemblies. In 1972, Minnesota DOT (MnDOT) pioneered coordinated ramp meters. The 1980's and 1990's saw the advent of early traffic responsive ramp meters. In 2006, Caltrans implemented area wide adaptive ramp meters in the Los Angeles area.

Currently, significant U.S. ramp metering deployments are in Miami, Fl.; Chicago, IL; Los Angeles, CA; Minneapolis/St. Paul, MN; New York, NY; Orange County, CA; Phoenix, AZ; Portland, OR; San Diego, CA; San Jose/San Francisco, CA; Seattle, WA; Denver, CO; Las Vegas, NV; Kansas City, MO/KS; Northern Virginia; Philadelphia, PA; Columbus, OH; Salt Lake City, UT; Milwaukee, WI, and Atlanta, GA. A number of other metropolitan areas currently run smaller ramp metering systems. Ramp meters are operational throughout Europe, with notable deployments in England, Belgium, France, Germany, and The Netherlands.

1.2. Ramp Meter Purpose

The main objective of ramp metering is to improve freeway efficiency. Ramp meters are a tool used to manage traffic on freeways by regulating the rate at which vehicles can enter the freeway, typically one or two vehicles at a time, in order to improve the average speed of all vehicles traveling on the freeway. Freeway capacity can exceed 2,000 vehicles per hour per lane (vphpl) during free-flow conditions, but can quickly drop to less than 1,500 vphpl during congested conditions. Ramp meters help balance freeway demand with capacity and prevent large platoons of vehicles from entering the freeway, which helps prevent or reduce flow breakdown on the freeway. Ramp meter implementation can increase the number of total vehicles accommodated by the freeway, making it more efficient. Although vehicles are briefly delayed at entrance ramp queues, the goal is that this delay will be negated by the overall reduction in travel time.

Ramp meters consist of traffic signals located on freeway entrance ramps that regulate the rate vehicles can access the freeway. The ramp-metering rate is based on historical data or real-time conditions obtained by vehicle detectors. Various methods and algorithms are used in different ramp metering operations based on the system's goals, which can include the following:

- Safer and smoother merging for vehicles entering freeways
- Reduced congestion
- Increased and steadier flow
- Increased speed
- Decreased delay
- Reduced vehicle emissions
- Improved ramp queue management to prevent spillback onto the crossing roadways
- Reduced rear-end and side swipe accidents

A secondary objective of ramp meters is to reduce freeway demand by discouraging freeway use for short trips during rush hour.

In contrast, some potential negative effects have been associated with ramp meters:

- Diversion of vehicles onto adjacent/parallel surface streets
- Long queues on entrance ramps
- An inequity of delay between ramps
- An inequity that favors commuters traveling from suburbs, who access the freeway from non-metered ramps, over drivers near the city center, who access the freeway from metered ramps.

Some ramp meter systems are coordinated in order to achieve equity of delay between ramps (see Section 3.1: Algorithms and Coordination). While this can reduce the system's efficiency, it allows for a fairer distribution of queue delays. Ramp metering algorithms are often used to prevent long queues from reaching the surface streets by using queue sensors to identify increases. The metering rate will then increase as the queue length increases or hits a critical length.

1.3. Ramp Metering Types

Four types of ramp metering operations are commonly used:

- Fixed time
- Local traffic responsive
- System-wide traffic responsive
- Adaptive

Each type of metering operation can be used with one of two modes:

- One car per cycle per lane metering – one vehicle per cycle is permitted
- Multi-lane ramp metering – ramp meter consists of two or more lanes that are metered
- Platoon metering – two to three vehicles per cycle are permitted (for use at freeway connectors or heavy ramps)

1.3.1. Fixed Time

Fixed time ramp metering is the most basic type of operation. The ramp metering period only operates at pre-set times of day, and the metering rate is fixed based on historical traffic data. A fixed time ramp meter does not respond to freeway mainline conditions—equal amounts of green time are given to entering vehicles, regardless of freeway traffic conditions. Some fixed time ramp meters can respond to excessive queue length and can override the metering rate by flushing the queue if it gets too long. An example of fixed time operation is found in California, where Caltrans typically uses fixed time ramp metering operations as a backup strategy when mainline loops are malfunctioning or during construction.

1.3.2. Local Traffic Responsive

Ramp metering using local traffic-responsive operations employs vehicle detection located on the entrance ramp and on the freeway mainline upstream of the ramp. One of the key features of local traffic-responsive meters is that the meter can turn on and off throughout the day as conditions dictate. The ramp meter operates at a set rate until freeway volume drops below a set critical volume and occupancy. The controller can then override the set metering rate to allow more cars onto the freeway. One downside to local traffic-responsive metering is that it considers only what is happening adjacent to the ramp, and does not consider what is happening on the rest of the system—notably downstream.

Some local traffic-responsive operations have the capability to manage demand rates when incidents occur on the freeway. (The queue management feature is discussed in more detail in Section 3.1, Algorithms and Coordination.) Queue management allows the ramp meter to decrease the metering rate (vehicles per green) at ramps upstream of the incident, and increase the rate at ramps downstream. This feature requires certain communications infrastructure to be installed.

The Georgia Department of Transportation (GDOT) primarily uses local traffic-responsive ramp metering—each ramp meter does not coordinate with any other ramp meter. However, all ramp meters are connected to the GDOT fiber network.

Las Vegas's FAST system operates a small number of ramps all day due to congestion and safety issues. Most of the FAST system ramps are set to operate during certain periods of the day. Within those periods, they operate in local traffic responsive mode. They have six traffic responsive settings available at each site.

1.3.3. System-Wide Traffic Responsive

This ramp metering method builds on the local traffic-responsive operation by adapting to conditions along the entire section of the freeway, not just adjacent to the ramp. System-wide traffic-responsive operation uses vehicle detection along the entire section of freeway in the ramp metering system. All ramp meters within the system are coordinated with each other to meter all vehicles entering the freeway and provide the best overall traffic management strategy. This method allows the metering rate at any ramp to be influenced by conditions at other ramps. System-wide traffic-responsive operation requires communications infrastructure that can connect to a centralized computer-controlled system. Denver, some California districts, and Portland are among the areas that use some type of system-wide traffic-responsive operation.

The choice of ramp meter control must consider a number of factors. If the congestion is limited to isolated or a very few ramps, a more appropriate control would be local operation versus an area or system wide control. If the congestion occurs at multiple locations that are close together and are largely contiguous, then an area or system-wide control would be more appropriate. Another factor is concern about equity where it may be perceived one area benefits at the expense of another. An example of this would be suburban users receive more benefit than urban areas where congestion is higher and the need for congestion mitigation is greater. If equity is a concern, then an area or system-wide control is more appropriate.

1.3.4. Traffic Adaptive

Traffic adaptive operation consists of metering rates being determined system or corridor wide using system or corridor wide data. The determination of the metering rate consider the corridor and upstream traffic conditions.

1.4. Operational Strategies

Ramp meters can operate based on one of three operational strategies. These strategies dictate the timing and capacity of the ramp meter. These strategies are:

1.4.1. Single lane, one car per lane per green

This strategy allows one car per green per lane. Research has found the typical capacity is between 240 and 900 vph. At 900 vph, this equates to a four-second cycle. Single lane, one car per green is by far the most common strategy.

1.4.2. Single lane, multiple cars per green

This strategy is sometimes referred to as bulk metering. Typically, the metering rate is two cars per green. The capacity is not substantially higher due to longer cycle lengths. The following Table 1 from TxDOT shows the timing and capacities for bulk metering

Table 1. Bulk Rate Ramp Meter Timing

Timing Interval	Vehicles per Green					
	1	2	3	4	5	6
Red (sec.)	2.0	2.0	2.32	2.61	2.86	3.08
Yellow (sec.)	1.0	1.70	2.0	2.22	2.41	2.58
Green (sec.)	1.0	3.37	5.47	7.35	9.13	10.83
Cycle Length (sec.)	4.0	7.07	9.79	12.18	14.40	16.49
Capacity (vph)	900	1018	1103	1182	1250	1310

1.4.3. Dual Lane Meters

As originally proposed in Texas, the dual lane ramp metering strategy is unique in that it requires a green, yellow, and red indication for each lane, Capacity can be up to 1700 vph. However, many states such as Arizona, California and others use red and green indications without a clearance indication.

Figure 1 provides a comparison made by TxDOT between these operational strategies. As ramp volume increases, all strategies converge on 1800 vph where the quality of service becomes poor due to very high demand.

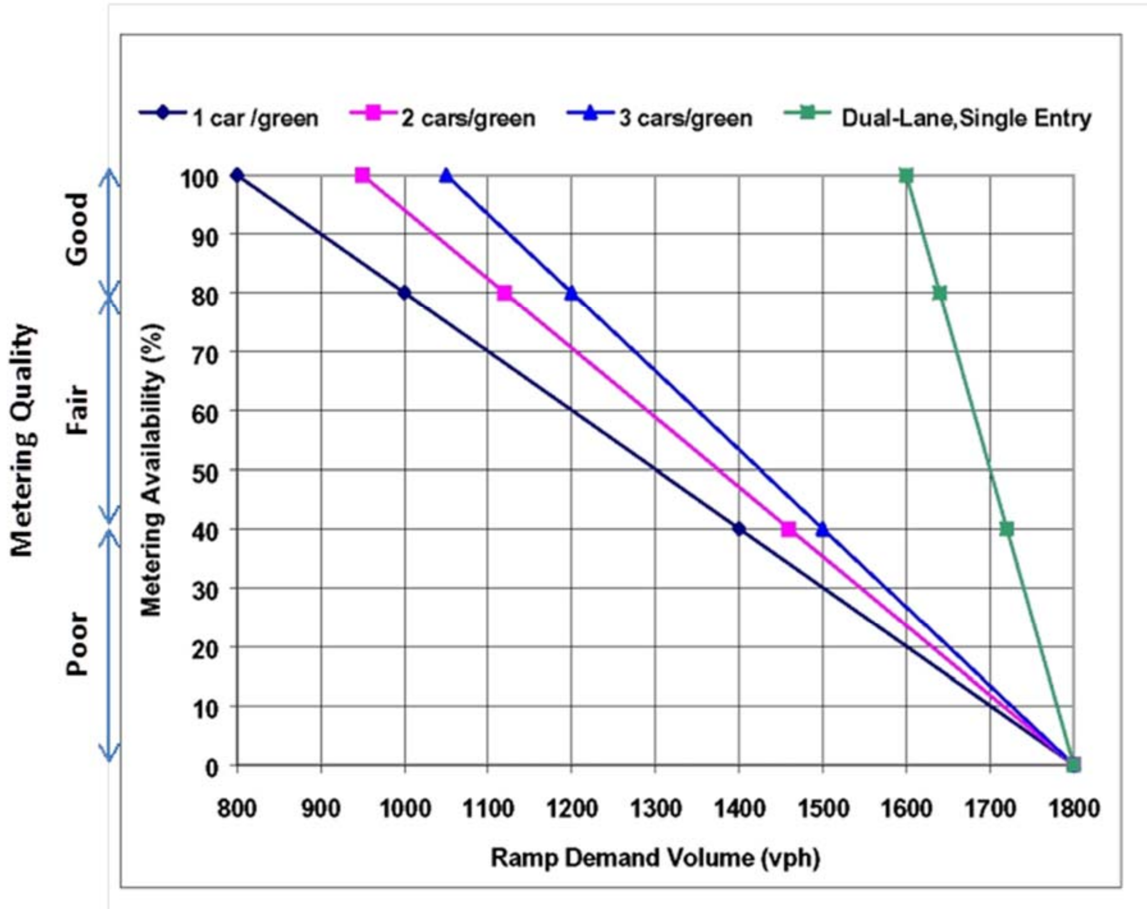


Figure 1. Ramp Meter Quality of Service and Capacity

2. Technical Research

2.1. Ramp Meter Site Selection

Optimal selection of a ramp meter site is based on physical ramp characteristics and freeway traffic characteristics.

A number of factors are considered in determining if a ramp is suitable for ramp metering operations. Different aspects of the ramp's physical site characteristics (length, number of lanes, shape, grade, and presence of an HOV lane) are considered in determining if a ramp meter is safe to install and would be beneficial. Other characteristics (ramp and freeway capacity, volume, speed, and accident history) are also considered in determining a beneficial ramp meter site. The following sections describe the physical and traffic characteristics that are typically considered when determining adequate ramp meter sites.

2.1.1. Physical Site Characteristics

The ramp meter stop bar must be located on the ramp where it can achieve balance between queue storage space and acceleration distance to the freeway. The three primary considerations for determining if a ramp's physical characteristics are suitable for metering are: (1) availability of queue storage space, (2) adequate acceleration distance and merge area beyond the meter, and (3) sight distance. Typically, adequate queue storage space is determined based on the ramp's projected volume. Adequate acceleration distance and sight distance are typically determined by AASHTO's *Green Book*, although some states have their own requirements. If queue storage is not adequate after establishing the stop bar location due to acceleration distance, this can be mitigated by using multiple lane ramp meters.

GDOT requires the stop bar to be placed upstream of the physical gore to discourage drivers from leaving the ramp meter queue and entering mainline traffic. GDOT suggests installing guardrail, barrier walls, retaining walls, a concrete-lined ditch, or a grassed area to discourage impatient drivers from leaving the ramp meter queue and merging directly into mainline traffic. Such illegal behavior can significantly reduce the effectiveness of the ramp meter, undermining its ability to help manage mainline congestion.

If queue storage space is an issue, adding a second lane to the ramp can allow for more storage. Wisconsin Department of Transportation (WisDOT) guidelines require the ramp to provide storage for a minimum of 10 percent of the current peak-hour volume.

Limited sight distance on many curved ramps makes it difficult to install a ramp meter and still meet the minimum stopping distance requirements. Ramps where minimum stopping distance cannot be achieved are not candidates for ramp meters. Ramp grade must be considered in determining adequate stopping distance and acceleration distance. A smooth merge area onto the freeway mainline is necessary because vehicles will be merging after coming to a complete stop.

2.1.2. Traffic Characteristics

A ramp meter will only be beneficial if the existing traffic conditions meet the criteria that ramp meters are designed to address. The fundamental purpose of a ramp meter is to improve an existing traffic congestion problem caused by merging traffic. The United Kingdom Highways Agency's Interim Advice Note states that a candidate site for a ramp meter should show flow breakdown on the mainline near the ramp if speeds drop below 30 miles per hour (mph) on a regular basis, causing appreciable delay.

2.1.2.1. Ramp Meter Capacity

It is important to note that improvement to freeway mainline congestion is most effective when the congestion is caused by merging traffic from the ramp or excessive demand downstream of the merge. The UK has found that ramp meters are most effective when freeway mainline flows are above 1,500 vph per lane and ramp flows above 400 vph per lane, but lower flows are acceptable for achieving beneficial results.

Arizona Department of Transportation (ADOT) has developed guidance for timing ramp meters as shown in Tables 2 and 3:

Table 2. ADOT Controller Timing Parameters

Interval Parameter	Controller Setting (seconds)
Min. Green	1.5
Max. Green	1.5
Min. Red	1.0
Max. Red	1.5

Table 3. ADOT Default Metering Rates

Metering Plan	Rate (veh./min.)	Rate (vph)	Cycle Length (sec.)
1	20	1200	3
2	18	1080	3.33
3	16	960	3.75
4	14	840	4.29
5	12	720	5
6	10	600	6

Similar to ADOT, The Las Vegas FAST system utilizes a maximum metering rate of 15 vehicles per minute per lane or 900 vehicles per hour per lane. For two lanes the maximum capacity of 30 vehicles per minute or 1,800 vehicles per hour per lane. They have found that with three lanes the capacity is limited at 1,800 vehicles per hour per lane. When FAST staff have installed triple ramp meters, they have done so due to limited storage distance as a two-lane ramp meter.

Texas Transportation Institute (TTI) developed, for TxDOT, guidelines for ramp metering and an evaluation for ramp meter algorithms.

2.1.2.2. Arizona Ramp Meter Warrants

The *Arizona Ramp Meter Design Guide* includes a systematic methodology for determining whether ramp metering is warranted. It describes a common, formal procedure that can be applied in a variety of candidate ramp metering cases to determine whether ramp meter deployment is appropriate. This process looks at ramps, surface streets, and ramp connections that might be affected by the ramp control as well as the freeway mainline section.

The process collects data of current mainline and ramp traffic volumes, predicted future mainline and ramp traffic volumes, collision data, and freeway and ramp operating speeds, and uses the data in a nine-step warrant process to determine if a ramp meter is a good candidate. Arizona's basic warrants stipulate:

1) Warrant 1: During a 15-min. period the freeway outside lane volume + ramp volume > 2,050 vph and the ramp volume > 400 vph.
2) Warrant 2: Freeway speed during a 15-min. period, mainline speeds (excluding HOV lanes) < 50 mph due to recurring congestion to or within 2 miles downstream of an entrance ramp.

2.1.2.3. Caltrans Criteria/Guidelines

Caltrans developed guidelines but not specific warrants for the installation of ramp meters. Each District updated a biennial plan for their deployment. Caltrans requires any new interchanges or interchange modifications to include provisions for ramp meters. Caltrans guidelines for ramp meters are as follows:

- Single-lane ramp meter geometry should be included for volumes up to 900 vph.
- When entrance ramp volumes exceed 900 vph, and/or when an HOV lane is determined to be necessary, a two- or three-lane ramp segment should be provided.
- Three-lane metered ramps are typically used for peak hour traffic along urban and suburban freeways.
- Ramp meters should be installed when the volume is between 240 and 900 vehicles per hour per lane.
- For ramps with peak-hour volume between 500 and 900 vph, a two-lane ramp meter may be used to increase the available storage.

2.1.2.4. Colorado DOT Guidelines

In the Denver area, Colorado DOT developed the following guidelines based on field observations and experience:

- If the combined mainline and ramp volume exceeds the following thresholds:
  - Two mainline freeway lanes with 2650 vph,
  - Three mainline freeway lanes with 4250 vph, and
  - Four mainline freeway lanes with 5850 vph.
- Single lane ramp meter when ramp volume is less than 900 vph
- Two lane ramp meter when ramp volume is greater than 900 vph

2.1.2.5. GDOT Ramp Meter Warrant Criteria

GDOT uses the following criteria in Table 4 when deciding to install a ramp meter. Additionally, as a general policy, all freeway and interstate highway entrance ramps will be metered within the metro Atlanta area, except freeway-to-freeway ramps and ramps to collector-distributors.

Table 4. GDOT Ramp Meter Warrant Criteria

Congestion V/C > 0.88	Collision Rate > 2.0 per million vehicles	Peak-hour Volume > 240 vehicles	Install Meter?
YES	ANY VALUE	YES	YES
YES	ANY VALUE	NO	NO*
NO	YES	YES	YES
NO	YES	NO	NO*
NO	NO	ANY VALUE	NO*

* Ramp meter is not essential, but may be installed for reasons other than those listed above.
Source: NET Corporation, June 2005

2.1.2.6. Nevada DOT

Nevada DOT developed a very comprehensive set of warrants that includes volume, speed, crash rate, and geometry. Many of the warrant criteria, as shown in Table 5 is similar to Arizona and California.

Table 5. Nevada Ramp Meter Warrant Criteria

Number	Name	Description
1	Ramp Volume Warrant (Ramp Volume)	Is the ramp volume during the critical peak period greater than 240 vehicles per hour per lane (vphpl)? 240 vphpl is the practical lower limit for ramp metering.
2	Safety Warrant (Crash Rate)	Is the rate of crashes at the ramp gore point or within 500 feet in either direction of the gore point greater than the mean crash rate for comparable sections of freeways in the metropolitan area?
3	Operational Warrant 1 (Speeds)	Does the freeway operate at speeds less than 50 mph for duration of at least 30 minutes for 200 or more calendar days per year?
4	Operational Warrant 2 (LOS)	Does the freeway operate at LOS D or worse during the peak period?
5	Volume Warrant 1 (Mainline Volume* and Ramp Volume)	Does the total volume* downstream of the gore during the peak period exceed the following: ◆ Two mainline lanes in one direction – 2,650 vehicles per hour (vph) ◆ Three mainline lanes in one direction – 4,250 vph ◆ Four mainline lanes in one direction – 5,850 vph ◆ Five mainline lanes in one direction – 7,450 vph ◆ Six mainline lanes in one direction – 9,050 vph ◆ More than six mainline lanes in one direction – 10,650 vph
6	Volume Warrant 2 (Mainline Right Lane Volume and Ramp Volume)	Is the ramp volume plus the mainline right lane volume downstream of the gore during the peak period greater than 2,100 vph?
7	Platoon Warrant (Platoons from Signalized Intersections)	Is the hourly volume entering from arterials, based on highest 30-second volume readings (during the critical peak period) projected to hourly values, greater than 1,100 vph?
8	Geometry Condition 1 (Acceleration Length)	Is the available or proposed acceleration length after the stop bar longer than the required acceleration length, or can geometric improvements be made to provide the required length?**
9	Geometry Condition 2 (Ramp Storage Length)	Is the available or proposed ramp storage length greater than the estimated queuing length on the ramp, or can geometric improvements be made to provide the required length?**

* Managed lanes are excluded. Only general-purpose lanes and auxiliary lanes that continue at least 1/3 mile downstream from ramp gore are included.

**Depending on the existing geometric conditions, and the required acceleration length and ramp storage length estimated for Warrants 8 and 9; geometric improvements may be needed prior to the implementation of the ramp meter.

2.1.2.7. New York DOT

New York DOT has similar criteria as Colorado, Arizona and California. New York's criteria is as follows:

- Ramp metering should be considered when freeways operate below level of service D. Freeway lane density generally should exceed 15 to 18 vehicles per mile.
- Adequate parallel surface routes must be available for the traffic diverted from the ramps to improve overall network performance.
- Adequate ramp storage capacity must be available to prevent queues of vehicles waiting to enter the freeway from blocking local street circulation.
- Ramp metering should not be applied where queues exist, e.g., at freeway lane-drops or convergence points, or at freeway-to-freeway connectors.
- One-lane ramp meters should be installed when the volume is between 240 and 900 vehicles per hour per lane.
- Two-lane ramp meters should be installed when the volume is between 400 and 1500-1800 vph.

2.1.2.8. WisDOT Ramp Meter Implementation Criteria

The WisDOT Ramp Metering and Control Plan describes the criteria recommended for a ramp meter deployment based on evaluating other states' requirements. WisDOT's plan recommends the following criteria:

- Freeway Volume – Vehicle flow rates of 1,200 vphpl, coupled with slow moving traffic along the freeway lanes.
- Ramp Volume – Ramp volumes of at least 240 vph (400 vph for two lanes).
- Speed – Multiple ramp metering case studies listed 30 mph or less as the common minimum freeway speed to warrant ramp metering.
- Safety – While no specific number or crash rate is mentioned in any of the previous reports, a reduction in accidents at the merge is often cited as the reason for ramp metering, and is used in the calculation of benefits.
- Ramp Geometric – Of the many geometric criteria established for ramp design, the three primary criteria include storage space, adequate acceleration distance and merge area beyond the meter, and sight distance. The FHWA *Freeway Management and Operations Handbook* (Chapter 7) and Wisconsin's *Intelligent Transportation System Design Manual* (Version 2) provide ramp requirement guidelines for the design of a ramp metering system.
- Funding – Before attempting to implement a new ramp metering project, an evaluation of potential funding sources should be completed to determine if there is sufficient support for the project.
- Alternate Route – An alternative route for motorists on the arterial network to avoid delays on entrance ramps created by a ramp meter.

2.1.3. Crash Data

Research found that other states have not used crash data as justification for ramp meter installations. Table 6 shows a summary of crash benefits for a select group of deployments in other states.

Table 6. Evaluation Results for Secondary Crash Benefits

Evaluation Result	Crash Reduction
Detroit, MI	-50%
Kansas City, KS/MO (SCOUT)	-26% to -50%
Los Angeles, CA	-20%
Minneapolis, MN	-26%
Milwaukee, WI	-16%
New York (INFORM)	-15%
Portland, OR	-43%
Seattle, WA	-38%

2.2. Ramp Meter Hardware

Ramp meter technology and equipment is not much different than the technology and equipment used at a typical signal-controlled intersection. The main differences arise from the location of the ramp meter on a freeway entrance ramp, and the purpose of a ramp meter as compared to a typical traffic signal at an intersection. This section describes the different technical components of ramp meter systems used by other agencies.

2.2.1. Ramp Meter Signals

Ramp meters must use traffic control signals that meet standard design specifications per the FHWA's *Manual on Uniform Traffic Control Devices (MUTCD)*, 2009 Edition. Ramp meter signals may be either three-section head (red, amber, and green) or two-section head (red and green). The *MUTCD* requires a minimum of two signal heads per ramp that face entering traffic for single-lane ramps, or multiple-lane ramps that operate with simultaneous green signal indications. Both signal heads may be mounted on the side of the roadway on a single Type I signal pole (vertical pole only). Some agencies use both a three-section head and a two-section head on the same signal pole. An additional status indicator light can be installed on the backside of the signal pole for enforcement. Las Vegas uses this backside indicator, sometimes referred to as a "tattletale" light.

Ramp meter signals may be put in dark mode (no indications displayed) when not in use. Some ramps have high-occupancy vehicle (HOV) bypass lanes that are not metered. These bypass lanes do not require traffic signals. When ramp meter signals are operated only during certain periods of the day, a *RAMP METERED WHEN FLASHING* (W3-8) sign should be installed in advance of the ramp meter signal near the entrance ramp or on the arterial on approach to the ramp. This sign will alert motorists to the presence and operation of ramp meters. When sight distance to the ramp meter signal or queue is impaired, advance warning signs with flashing beacons should be installed.

Ramp meter signals may be accompanied by regulatory signs indicating if the ramp meter is currently in use, how many cars may go on green, or other instructions. Often these regulatory signs are variable message signs (VMS), which allow the agency greater flexibility in controlling the ramp meter's operation.

2.2.1.1. California Ramp Meter Signals

California uses two, three-section heads (300mm lenses) or a combination of a three-section head (300 mm lenses) and a two-section head (200 mm lenses) for each lane of a metered ramp in Figure 2. The use of the three-section or two-section head depends on the type of ramp metering output. The three-section upper head is used for "two cars per green" output, and the lower two-section head is used for "one car per green" output. Additionally, a one-section head used as a signal status indicator is installed on the backside for enforcement. A single-lane ramp requires the pedestal to be mounted on the left side of the ramp, where dual-lane ramps require a pedestal on each side of the ramp. California allows for the use of wall-mount or mast arm signals, if needed. The signal and stop bar are located in order to meet minimum acceleration lengths required by AASHTO's *A Policy on Geometric Design of Highways and Streets ("Green Book")*.

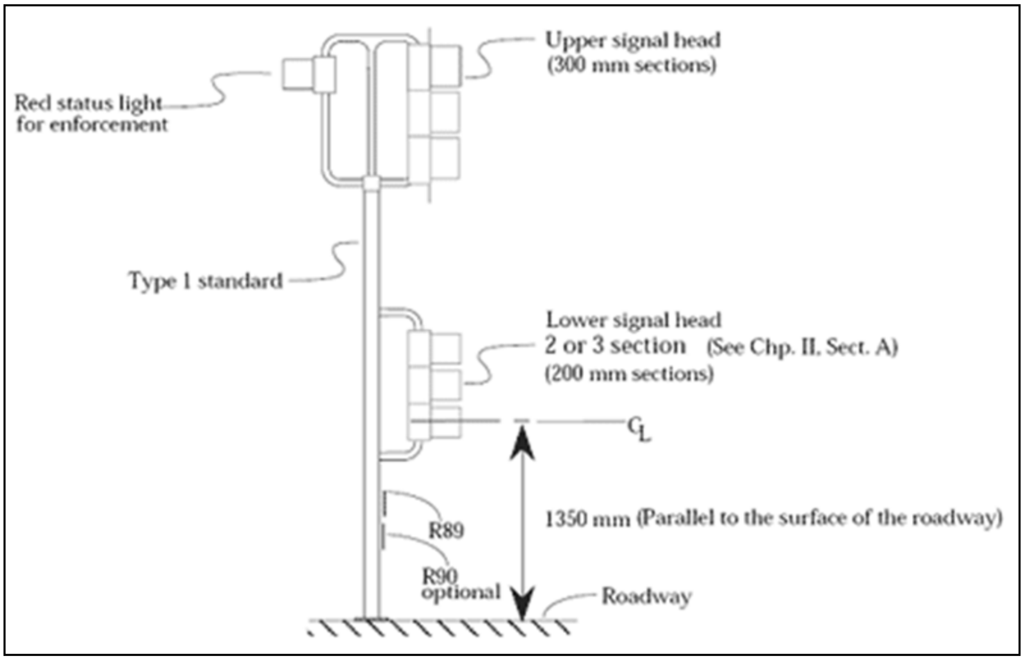


Figure 2. Typical Signal Standard used by Caltrans (NTS)

2.2.1.2. Georgia Ramp Meter Signals

Georgia ramp meter signals consist of two, three-section heads mounted on a pedestal signal pole for a single-lane ramp. The upper-mounted signal head is a 12-inch display facing

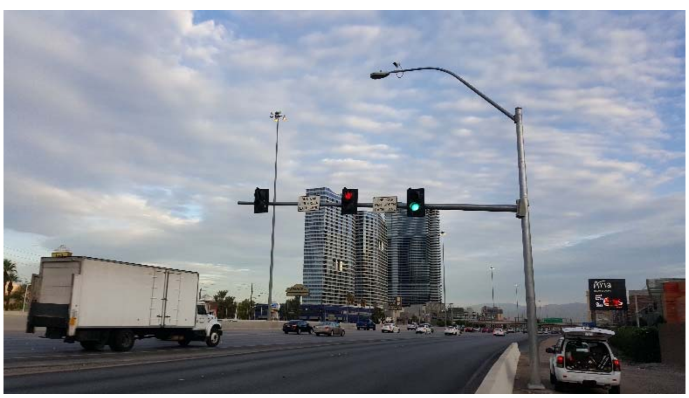
upstream, and the lower-mounted signal head is an 8-inch display facing the waiting vehicle. The upper 12-inch display contains an enforcement display facing downstream (see photo at right).

Multi-lane entrance ramps contain a mast-arm signal pole with two, three-section heads per lane; one signal per lane has an accompanying enforcement indicator for downstream visibility. The mast arm is located about 60 feet downstream of the stop bar in order to meet minimum acceleration lengths required by AASHTO's *Green Book*.

2.2.1.3. Arizona Ramp Meter Signals

Arizona uses two-section heads, with two heads on each signal pole. The upper two-section head is a 12-inch light-emitting diode (LED) signal head that is mounted at a 10-foot elevation; the lower two-section head is an 8-inch LED signal head mounted at a 4.5-foot elevation. The lower head faces the vehicle at the stop bar; the upper head faces vehicles that are 300 feet upstream of the stop bar. A "One Vehicle per Green" sign is mounted on the signal pole between the two signal heads. Additionally, a 2-inch red LED enforcement indication is mounted at a 10-foot elevation, facing the downstream enforcement area. The stop bar is located in order to meet minimum acceleration lengths required by AASHTO's Green Book.

2.2.1.4. Las Vegas Ramp Meter Signals



The Las Vegas metro area ITS system is called FAST. Some of their ramp meters on the older freeways do not have the ideal acceleration distances. Their ramp meters use two section 12-inch signals. For single lane ramps, they use post or mast arm mounted signals. For two lane ramps, they prefer to mount the signals overhead. For three-lane ramp meters, overhead mounting is required since they operate with one car per lane per green. All ramp signals have a white tattletale light on the back of each signal head for downstream enforcement.

2.2.1.5. Minnesota Ramp Meter Signals

Minnesota ramp meter traffic signals are mounted 300 to 600 feet upstream from the point where the ramp and the freeway merge. The meters use two, three-section 8-inch heads that are mounted on each signal pedestal. The upper signal head is mounted at a 10-foot elevation and aimed at vehicles entering the ramp. The lower signal head is mounted at a 5-foot elevation, aimed at the stop line. A single-lane ramp requires that the pedestal be mounted on the left side of the ramp; dual-lane ramps require a pedestal on each side of the ramp.

2.2.1.6. Oregon Ramp Meter Signals

Oregon prefers to pedestal mount the ramp meter signals on breakaway pedestals unless there are more than two controlled ramp lanes, physical constraints, or when the stop line is located beyond the physical gore point. Oregon uses one three-section and one two-section signal head on each pedestal. They utilize the strategy “one vehicle per green.” Oregon also uses the advance sign “Ramp Metered When Flashing” with yellow beacons. If there is limited sight distance, they use sign “Be Prepared to Stop” with yellow beacons. If a ramp is two lanes, then they use a sign “Form 2 Lanes When Metered.”

Oregon DOT uses the new ATC controller for ramp meters.

2.2.1.7. United Kingdom Ramp Meter Signals

The United Kingdom uses two signal heads at eye level that are turned to face the driver, and two high-level signal heads that face up the entrance ramp. Each signal head has three indications (red, yellow, and green) and a yellow back plate to distinguish it from standard traffic signals.

2.2.1.8. European Ramp Meter Signals

- Belgium: Three indication signal heads with yellow back plates are used. A flashing yellow signal indicates that the system has been switched off due to excessive queues. Signs on the entrance ramp explain how the system works.
- Germany: Three indication signal heads with yellow back plates are used. The signals are switched off when not operational.
- France: Two indication signal heads (red/yellow) with a yellow back plate are used. A warning sign with a flashing yellow signal installed at the ramp entry indicates when ramp metering is operational.
- The Netherlands: Three indication signal heads with yellow back plates are used. A warning sign with a flashing yellow signal installed at the ramp entry indicates if ramp metering is operational. The ramps are switched off when not operational.

2.2.2. Ramp Meter Vehicle Detection

Responsive traffic ramp metering for local and system-wide operation requires several vehicle detectors on both the freeway mainline and on the ramp as shown in Figure 3. Fixed time operation ramp meters rely on historical or predicted traffic data and use only vehicle detection on the ramp for queue management or to actuate and terminate the metering cycle. Traditionally, detection has been implemented in the form of induction loops; however, other detection devices can be used if they are more suitable to the agency and the environment.

In Atlanta, GDOT uses inductive loop detection on ramps and video detection on freeway mainlines to avoid the hazards related to installing loops on an operating freeway. The video detectors are placed to detect mainline traffic conditions in the four outermost travel lanes, 50 to 500 feet upstream of the ramp gore where meters are proposed. GDOT also requires a closed-circuit television (CCTV) camera to view the ramp meter stop bar and discharge area of each ramp meter location. When possible, the CCTV camera is installed on the same pole as the vehicle detection cameras. GDOT has indicated that video detection on the mainline has been effective.

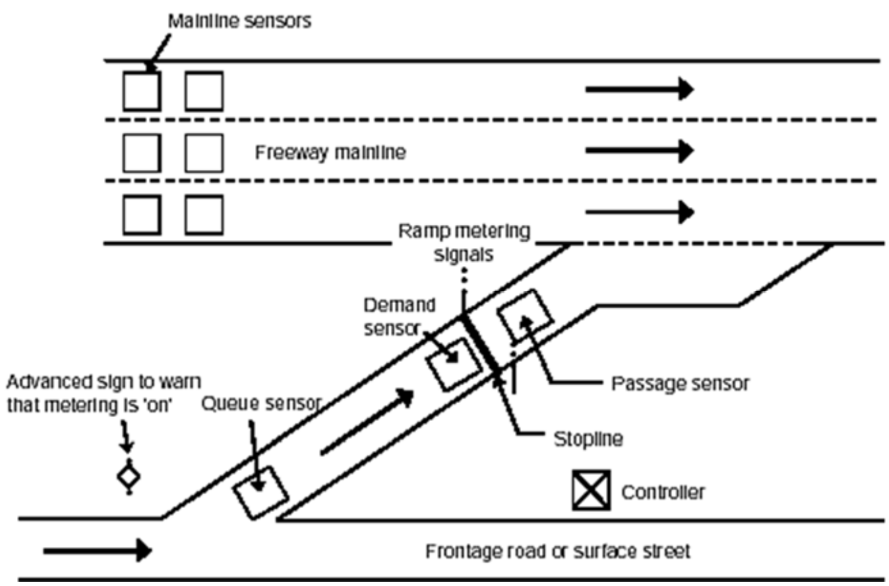


Figure 3. Conceptual Ramp Metering Detector Configurations

Southern Nevada uses inductive loop detection on ramps and microwave radar detection on freeway mainlines to avoid hazards related to installing loops on an operating freeway. They have tried video detection but not found that to be satisfactory. Significant CCTV coverage at ramp meter locations allows the agency to monitor ramp meter activity and control the ramp meter operations as necessary.

Ramp meter detectors are located based on the detector's function, which include demand, passage, ramp queue, mainline, exit ramp (system-wide metering operations only), and entrance ramp without meter (system-wide metering operations only).

Demand detectors, located just upstream from the stop bar, detect the presence of a vehicle at the ramp meter and initiate the ramp metering cycle. Passage detectors are located just downstream from the stop bar to detect and count the number of vehicles entering the freeway, which can be used to determine the duration of the green signal display.

Queue management detectors, located near the ramp intersection and the adjacent surface street, monitor excessive queues that exceed the ramp storage capacity. If the detectors identify that ramp queues are about to back up onto surface streets, they will increase the metering rate or temporarily terminate ramp metering operations. Additional intermediate queue detectors can be located along the ramp to monitor ramp queues and attempt to flush the queue before it backs up to the surface street.

Table 7 summarizes the type, purpose and placement of ramp meter detection.

Table 7. Typical Ramp Meter Detection

Detector Type	Purpose	Siting Criteria
Freeway Mainline	Freeway volume, speed and occupancy	Upstream or downstream of ramp merge depending on algorithm
Queue	Detect excess queue to invoke queue management detection	Upstream end of ramp
Demand	Detects vehicle presence to service the lane	Upstream of stop bar
Passage	Extends green for certain software	Downstream of stop bar

To determine the optimal metering rate, freeway mainline detectors are used to monitor the freeway flow rate and speed. In local ramp metering operations, mainline detectors are located upstream of the entrance ramp gore point. System-wide metering operations can use mainline detectors downstream of ramps as well. The United Kingdom ramp metering systems use existing detection loops along the freeway mainline. Optimum detection loops are chosen for monitoring upstream and downstream of the merge area. Up to 12 sets of loops can be installed on the entrance ramp for queue management purposes.

2.2.3. Controllers and Cabinets

Just as each traffic signal-controlled intersection requires a controller cabinet assembly, each ramp meter location also requires a controller cabinet. Equipment required for a ramp meter cabinet is similar to a controller cabinet at a traffic intersection. Cabinet location requirements, such as clear zone, maintenance pad, and safety requirements, are typically the same for ramp meter cabinets and traffic signal cabinets. In Arizona, ramp meter cabinets are required to be located a minimum of 20 feet upstream of the stop bar, so that the ramp signal heads are visible from the front door of the cabinet. Cabinet location should also comply with distance requirements for inductive loop detectors, if used.

Ramp meters are controlled by traffic signal controllers operating with specialized software embedded in the controller (firmware), which differs from traffic intersection control firmware.

This firmware operates the ramp metering strategies employed. Arizona uses a Model 170 controller unit that contains firmware by Bi Trans Systems developed for the Arizona Department of Transportation. Arizona requires the Model 170 controller be equipped with non-volatile random-access memory and battery backup to ensure that the ramp timing parameters are not lost in the event of a power outage.

California and Oregon require a Model 170 or a Model 2070 controller. FAST in Las Vegas uses Model 170 controllers. The 2070 controllers provide similar functions to the 170 controller, but are more powerful and can provide additional functionality. GDOT uses 2070L controllers.

Ramp meter control cabinets can contain communications equipment, such as a modem or fiber-optic patch panel, to monitor and communicate with the controller from the transportation management center (TMC). This allows traffic control operators to remotely control ramp meter functions.

2.2.4. Signing and Marking

The presence of ramp meters can often be unexpected by approaching drivers. Advance-warning signs and markings can help inform motorists that they are approaching a ramp meter, thus preparing the driver to come to a stop before entering the freeway. In Kansas City, flashing yellow lights located near the ramp entrance alert motorists that the ramp is being metered and that they should be prepared to stop. California employs advance-warning devices at ramps where sight distance to the ramp meter signal or queue is impaired, and recommends that advance warnings be placed at all locations to indicate that metering is operational. California's advance warning devices typically consist of a flashing "SIGNAL AHEAD" beacon and an internally illuminated "METER ON" sign beneath the beacon.

Signs and road striping at the ramp meter indicate where to stop and how to proceed. Typical signs instruct the motorists to "STOP HERE ON RED" or "ONE CAR PER GREEN," depending on the ramp metering method used (e.g., "TWO CARS PER GREEN," "ONE CAR PER GREEN EACH LANE," etc.). Arizona uses an additional sign for metered ramp lanes—"ALL VEHICLES STOP ON RED."

Some ramp meters have HOV preferential lanes that allow carpools, buses, or other preferred vehicles to bypass the ramp meter as shown in Figure 4. These lanes are indicated by signs and pavement markings. California has HOV signs that include "WHEN METERED" to indicate single-occupancy vehicles are allowed in these lanes during non-metering periods and allowed to bypass the ramp meter. Arizona DOT also employs HOV-Equipped Ramp meters.

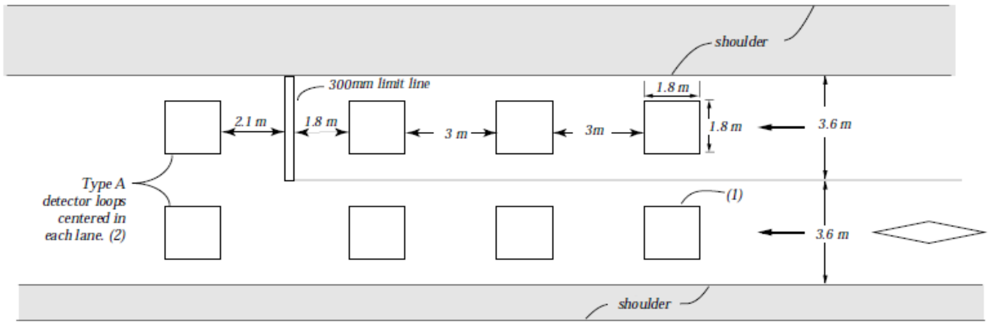


Figure 4. Caltrans Diagram of Two-Lane Ramp With Non-Metered HOV Lane

2.3. Ramp Meters and Managed Lanes

One of the principal interests of this research is to understand the potential interaction of managed lanes and ramp meters. Managed lanes can include:

- High Occupancy Lanes (HOV) lanes
- High Occupancy Toll Lanes (HOT) lanes
- Express Lanes with or without toll lanes
- Bus Only Lanes

Numerous states have used both some form of managed lanes and ramp meters together on freeways to mitigate congestion. These states include Arizona, California, Florida, Georgia, New York, Minnesota, Oregon, Texas, Virginia, Utah, and Wisconsin. Historically, most of these were HOV lanes. Many HOV lanes have been converted to some variation of toll lanes. HOV bypass lanes are a design element of many states' ramp meter design standards. HOV bypass lane design standards were developed for the *Ramp Meter Feasibility Study for Durham and Wake Counties*.

In the UK, HOV lanes are rare but one ramp metering site has been installed in the vicinity of an HOV lane which bypasses the ramp meter; it is due to be switched on in 2016 as a trial.

Of particular interest is the combination of ramp meters and tolled express lanes. I-77 and I-485 will have express lanes that are not barrier separated. The express lanes will be delineated by a combination of striping and flexible tubular markers. This is very similar to what GDOT deployed in Atlanta. GDOT deployed the ramp meters prior to the deployment of the express lanes.

Ramp meters and managed lanes can and do coexist on many freeways. Nevada DOT has developed a design manual and implementation plan that considers both on their freeways.

A critical design element of managed lanes is the placement of the entrance and exit points. The access points to the managed lanes should not be located to create weaving to and from the entrance and exit ramps. Such weaving creates additional congestion and safety problems.

2.4. Preemption

FAST has a unique situation where one of its major fire stations that serve the freeway system is located very close to a metered freeway ramp. During peak period operation, that ramp is very congested and further restricted by barrier walls. In order to clear the ramp, FAST staff installed a preemption link tied to the fire station doors that triggers the ramp meter controller to implement a plan to clear the ramp. This preemption is accomplished outside of the software because the software was not capable of preemption.

3. System Software

3.1. Algorithms and Coordination

Ramp meter algorithms are used to determine the metering rate in traffic-responsive systems. Algorithms can be as simple as a table lookup function or as complex as a formula that considers many conditions. The ramp metering operation type determines the type of algorithm needed for the ramp meter to function to its full potential. Accurate data from vehicle detectors are key to variable ramp meter algorithms. Table 8 shows a summary of ramp meter operation algorithms. When there is communications infrastructure between TMCs and the ramp meter controllers, the TMC operator can control the ramp meter operation remotely using ramp meter software that resides at the TMC and interfaces with the ramp meters in the field.

Ramp meter operation can be a combination of these algorithms. For example, many agencies use a time of day schedule to turn on or off the ramp meters and then during the time they operate they are in traffic responsive mode.

3.2. Software

There are numerous software vendors. Most states who have ramp meters use a single software. However, Caltrans has ramp meters in ten of the twelve districts. They use six different software packages and are moving to a single statewide package.

3.2.1. Fixed-Time Ramp Metering

Algorithms are not used for fixed-time ramp metering. The metering rate is pre-set for different times of day based on historical or predetermined traffic data. Fixed-time ramp meter algorithms do not consider real-time freeway mainline traffic.

3.2.2. Local Traffic-Responsive Ramp Metering Algorithms

More complex algorithms are used for determining the metering rate for local responsive ramp meter control, based on real-time traffic conditions on the freeway mainline adjacent to the ramp. It follows the concept that if the freeway volume falls below a predetermined value, then the ramp meter increases the metering rate to allow more cars to enter the freeway from the ramp. If the freeway volume increases to a predetermined value, then the ramp meter decreases the metering rate, reducing the amount of cars allowed to enter from the ramp. Freeway volume, speed, capacity, and other factors can be used in the algorithm to determine the metering rate that best serves the goals of the ramp meter.

3.2.3. System-wide Traffic-Responsive Ramp Metering Algorithms

System-wide algorithms are more complex and are used to coordinate a group of ramp meters to operate as an integrated system. This allows the ramp meters to balance queue delay and better manage bottlenecks and congestion. Algorithms used in system-wide ramp meter control require communicating the real-time traffic data to a central computer system to determine the optimum metering rate for each ramp in the system. System-wide ramp metering algorithms can also coordinate metering rates throughout the system in order to balance wait times and queue lengths.

3.2.4. Traffic Adaptive

The goal of traffic adaptive operation is to predict or anticipate future conditions and establish metering rates to mitigate those conditions.

Table 8 summarizes the ramp operation, detection requirements, benefits and limitations.

Table 8. Summary of Ramp Meter Operation Type

Ramp Meter Operation Type	Algorithm	Vehicle Detection Required	Benefits	Limitations
Fixed Time	Simple– typically set to time of day based on historical or predicted volumes.	Only to detect presence at stop bar on ramp. If queue management is used, additional detectors are required upstream on ramp.	Simple ramp metering strategy. Can be used if communications are temporarily down, if mainline vehicle detectors are malfunctioning, or during construction.	Does not respond to real-time changes in mainline traffic volume. Atypical events, such as crashes or lane closures, are not accounted for. Does not consider whole freeway system.
Local Traffic Responsive	Metering rate adjusts based on current conditions on freeway adjacent to ramp.	Detectors located on ramp and on freeway either adjacent to ramp or downstream of ramp.	Responds to real-time traffic conditions near ramps. Does not require communications to central TMC.	Does not consider freeway conditions in the rest of the system.
System-wide Traffic Responsive	Complex algorithms are used to determine each ramp's optimum metering rate in order to benefit the system as a whole.	Detectors located on ramps and along entire ramp metering section of freeway.	Responds to real-time traffic conditions throughout the entire system. Can prevent or reduce bottlenecks downstream of a ramp. Has potential for most benefit of all metering operations.	Requires communications to central computer system at TMC to operate. Communications or central computer failure can take system off-line. Has potential to favor some ramps over others, creating inequity issues.
Traffic Adaptive	Metering rates adjusted based predicted corridor or system wide conditions	Detectors located on ramps and along entire ramp metering section of freeway.	Has potential to be an improvement over traffic responsive	Requires communications to central computer system at TMC to operate. Communications or central computer

Ramp Meter Operation Type	Algorithm	Vehicle Detection Required	Benefits	Limitations
				failure can take system off-line. Has potential to favor some ramps over others, creating inequity issues.
Note that queue management strategies can be used with all ramp meter operation types.				

3.2.5. Examples of Specific Algorithms

- ALINEA is a ramp metering strategy that uses local feedback. ALINEA is used in local control. It attempts to maximize freeway mainline throughput by maintaining a desired freeway occupancy. It requires only one freeway detector per lane downstream of the entrance ramp. ALINEA provides closed-loop traffic responsive control where metering rates are calculated to maintain desired occupancy. The algorithm assumes that vehicles from the meter reach the detector within a measured time.
- BOTTLENECK is a centralized algorithm that provides local and system-level control on a selected freeway section. The local metering rate is selected from a look-up table based on the evaluation of upstream demand and downstream capacity of the freeway. System metering rate is based on system capacity constraints. The system-level control identifies a bottleneck, determines the volume reduction needed to reduce or eliminate the bottleneck, and then distributes this reduction to upstream ramps according to predetermined weights. This algorithm has been used in Seattle, Washington, for a number of years.
- Corridor Adaptive Ramp Metering Algorithm (CARMA) is a system-wide adaptive strategy used on the Kansas SCOUT program. Mainline speeds and local ramp conditions establish the metering rate based upon the logic that maximum volume occurs when the mainline speed is high.
- The Fuzzy Logic algorithm is a system wide control type and uses ramp queuing and more data inputs to allow more flexibility in establishing metering rates. A fuzzy logic algorithm is used in Seattle and Miami.
- RAMBO was developed by the Texas Transportation Institute for use by the Texas Department of Transportation. It consists of two programs—RAMBO I and RAMBO II. RAMBO I evaluates plans generated based on ramp metering specifications. RAMBO II is a system ramp metering package that evaluates metering rates based on forecasted traffic conditions along a section of freeway containing up to 12 metered entrance and exit ramps. RAMBO II uses an optimized linear programming model.
- Stratified Zone Metering (SZM) utilizes density measurements upstream of the merge, at exit ramps and on the mainline with the goal of having more vehicles exit than enter the freeway to relieve congestion. This algorithm is used in Minneapolis
- System-Wide Adaptive Ramp Metering (SWARM) is used in Portland, Oregon and Orange County, CA. It is a system wide adaptive strategy based upon current and required vehicle density. Ramp meters operate so the wait times is more evenly distributed.

- ZONE is an algorithm that divides a freeway into several zones (3 to 6 miles in length). The upstream end of the zone is a free-flow area, and the downstream end is treated as the critical bottleneck. This algorithm calculates metering rates based on volume control in each zone.

3.3. Queue Management

Queue management algorithms are used in almost all ramp metering systems. The algorithm mitigates queuing on the ramp to prevent traffic from backing up to the crossroad and potentially causing a safety hazard and local street congestion. It also prevents drivers from experiencing excessive queue delay that can cause frustration. As the queue builds to an unacceptable length, the algorithm increases the metering rate to reduce the queue. If the queue reaches a critical predetermined level, the ramp meter shuts off to reduce the queue, even though it may have negative effects on the freeway operation. Queue management also improves the fairness of ramp metering by giving priorities to vehicles in a long queue.

The Minneapolis/St. Paul ramp metering system in Minnesota applies both a queue length constraint and a restriction entrance ramp delay, which ensures that the waiting time at entrance ramps does not exceed 4 minutes.

The United Kingdom uses two algorithms for handling ramp queues. Queue management aims to maintain the queue at a desired level, and queue override detects if the queue is in danger of backing onto local roads and applies the maximum release rate. There is no mechanism to switch off metering if the queue backs onto local roads; however, due to efficient queue management and override strategy, this has not been required.

The UK system includes an option for the ramp meter to communicate with the traffic signal controller on the surface street. This provides basic information (one direction only) about the queue length on the ramp, which allows the traffic signal controller to alter its signal timings when the queue gets long, to allow ramp metering to continue working effectively for a longer period Although this slightly increases the surface street queues, the total delay can be reduced in this way. The system is only used at a handful of sites. However a project started in 2015 (Collaborative Traffic Management) which aims to provide a more sophisticated communication between ramp meter and surface street signal controllers to improve the performance of the most congested junctions. This will include the design of a new ramp metering controller.

3.4. Equity of Delay

The ramp control algorithm that produces the most efficient average travel time may not be the best algorithm in practice. Equity of delay between ramp meters must also be considered. While improving freeway efficiency is the most important goal of ramp metering, equity should be the second objective. Ramp metering algorithms may tend to favor some ramps over others by having different metering rates at different ramp sites. This can cause a variance in queue delay throughout the ramp metering system. Inequity of ramp meter delay was one concern voiced by citizens in the Minneapolis/St. Paul region, which precipitated a 6-week-long ramp meter evaluation period (discussed in Section 8.5). Minnesota Department of

Transportation implemented more restrictive maximum queue delay times and queue lengths in order to lessen inequitable ramp meter operations.

Denver uses a strategy known as a “helper algorithm” that applies more restrictive metering rates at upstream ramps in order to relieve a downstream ramp operating at a more restrictive rate.

4. Implementation

Ramp meter implementation involves activities before, during, and immediately after the period for which strategies are physically deployed and operated (Figure 5). Successful implementation is crucial to avoid the loss of public support. Wisconsin includes a section in its ramp control plan titled "Implementation Challenges," which describes public opposition as the main challenge to ramp metering implementation. However, it does not give direction on ways to deal with these challenges. The United Kingdom Highways Agency employs a suite of documents covering technical design, installation, configuration, calibration, operation, and handover of ramp metering sites. Calibration of new systems can take up to 2 weeks, and some sites require re-calibration as the traffic situation changes.

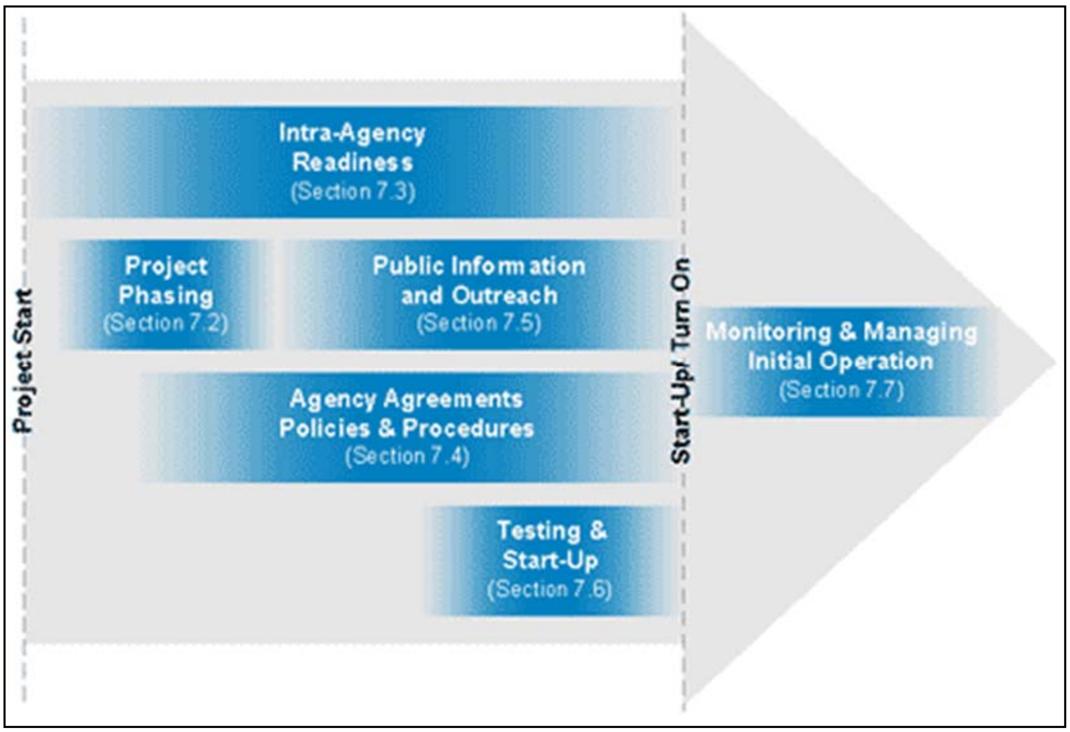


Figure 5. General Activities and Timeline for Ramp Management Strategy Implementation from FHWA *Ramp Management Handbook*

5. Design Standards

5.1. Federal Highway Administration

The FHWA *MUTCD* 2009 Edition describes ramp metering standards in Chapter 4I: Traffic Control Signals for Freeway Entrance Ramps. The *MUTCD* briefly covers the application, design, and operation of freeway entrance ramp control signals. A more robust and detailed analysis of ramp metering practices and design procedures are found in the FHWA's *Ramp Management and Control Handbook*, although the handbook does not constitute a standard, specification, or regulation. Major chapters and topics covered in the FHWA *Ramp Management and Control Handbook* include the following:

- Ramp Management and the Traffic Management Program
- Preparing for Successful Operations
- Ramp Management Strategies
- Developing and Selecting Strategies and Plans
- Implementing Strategies and Plans
- Operation and Maintenance of Ramp Management Strategies
- Ramp Performance Monitoring, Evaluation, and Reporting
- Planning and Design Considerations
- Case Studies

5.2. United Kingdom Highways Agency

The United Kingdom Highways Agency developed the *Ramp Metering Technical Design Guidelines* (2008) that provides extensive details on the design processes required to implement ramp metering systems. The document covers the following topics:

- Site Selection
- Examples of Ramp Meter Congestion Problems
- Ramp Meter Limitations
- Ramp Meter Components
- System Algorithms and Operation
- Ramp Meter Design
- Future Enhancements

States that employ ramp meters will typically have their own ramp meter design guides, which can often be found on the agencies' websites. The following is a description of the major chapters and topics covered by some of these ramp metering design guides.

5.3. Arizona Department of Transportation - *Ramp Meter Design Guide*

- Ramp Meter Warrants
- Ramp Meter Design
- Ramp Meter Operation
- Ramp Meter Maintenance

5.4. California Department of Transportation - *Ramp Meter Design Manual*

- Design of Metered Ramps
- Ramp Meter Hardware
- Signing and Pavement Markings
- Ramp Metering Policy Procedures

5.5. Nevada Department of Transportation - *Managed Lanes and Ramp Meter Design Manual*

- Part 1: Introduction and Policies
  - Metering Policy Procedures
- Part 2: Design of Metered Ramps
  - Ramp Meter Hardware
  - Signing and Pavement Markings
- Part 3: Implementation Plan

5.6. Oregon Department of Transportation - *Traffic Signal Design Manual*

- Operation
- Signalization and Head Mounting
- Signing and Pavement Markings
- Detection

5.7. Wisconsin Department of Transportation - *Ramp Metering and Control Plan*

- Literature Review
- Develop and Apply Methodology
- Assess Operational Feasibility
- Criteria Thresholds and Implementation Plan

6. Costs

Research was conducted to ascertain the various cost elements of ramp metering including hardware, software, firmware, equipment, maintenance, and operations.

6.1. Capital Costs

Capital costs include equipment such as controllers, cabinets, signal heads, and detection devices. In 2003, ADOT estimated a two-lane ramp meter cost of $60,000 each. More recently, Colorado estimated a ramp meter cost of $50,000.

The FHWA ITS Joint Program Office maintains a database of cost and benefit data. In that database the following data was reported in Table 9:

Table 9. ITS Joint Program Costs Database

Date	Agency	Description	Capital Cost	O&M Unit Cost
2007	Caltrans	Ramp Meter (two ramp lanes, 4 freeway lanes) complete	$ 169,800	$ 3,780
2003	FDOT (Miami)	Ramp meter assembly/signal display and the controller, no detection	$ 12,700	$ 1,196
2003	ADOT (low estimate)	Low estimate for ramp meter assembly/signal display, the controller, wiring, and MOT.	$ 54,000	n/a
2003	ADOT (high estimate)	High estimate for the ramp meter assembly, signal display, the controller, wiring, and MOT.	$ 64,000	n/a
2009	Kansas City SCOUT	Adaptive ramp metering system that includes a roadside warning beacon and a stop bar used to trigger the ramp meter signal.	$ 30,000	n/a

Date	Agency	Description	Capital Cost	O&M Unit Cost
2010	Washington DOT (high estimate)	Single ramp meter (high estimate)	$ 100,000	n/a
2010	Washington DOT (low estimate)	Single ramp meter (low estimate)	$ 10,000	n/a
2008	Caltrans (San Francisco)	Ramp Meter cost, including both signal and controller	$ 40,000	$ 2,000

NCDOT already procures most of this equipment for traffic signal installations and has developed a good cost history, which is available through the NCDOT website.

6.2. Program Costs

Program costs include central software, controller firmware, integration, training, and central hardware (servers and other communications equipment). FDOT, the Kansas SCOUT program, a prominent software vendor, and GDOT provided current information on the costs of ramp metering central software and firmware in Table 10.

Table 10. Program Costs

Description	Cost
Central Software and Installation	$ 135,000
Driver and Installation	$ 95,000
Integration	$ 110,000
Training	$ 20,000
Total	**$ 360,000**

A vendor quote estimated the firmware cost for the controllers at $50,000. Firmware installation and setup typically takes 1 day, and calibration should take 2 days per site.

6.3. Maintenance Costs

Maintenance costs include the cost of labor and materials to maintain the ramp meter equipment, and the cost of software support.

ADOT estimated in 2003 maintenance costs were $1,000/yr. Kansas DOT and GDOT provided newer estimates of their annual maintenance costs. In addition, data available through project reports and evaluation studies provided additional data points, although many of those costs were unusually low and not well defined as to what is included or excluded, even after adjusting to present day costs. Based upon an average of Kansas and GDOT's costs, annual scheduled (preventative) maintenance as well as unscheduled repairs is estimated at $6,400 per site. This amount was derived from an average cost of Kansas and GDOT's total costs divided by the number of ramp meters each state has implemented.

In 2010, FDOT reported annual maintenance cost per ramp meter as $3,500.

In addition, FDOT, Kansas DOT, and a prominent ramp metering vendor estimated an average of $24,000 per year for software support.

6.4. Operations Costs

Operations costs include staff time to monitor the ramp meter operation and respond to operational issues, adjustments in timing and operational parameters, and program management. NCDOT staff would monitor the ramp meter sites from the Statewide Transportation Operations Center (STOC) and respond appropriately. Based on an average of the information from Kansas DOT and GDOT, they spend about 24 hours per site per year monitoring and responding to timing types of issues. This equates to:

2 engineers x $50,000/each/167 = $600 per site per year.

7. Marketing and Outreach

Agencies with ramp meter deployments state that public support of ramp meters is essential for a successful implementation. Opposition toward ramp metering usually stems from the public's perception that delays occur because of ramp metering, while the associated benefits may not be obvious. Agencies have altered this perception through persistent public communication and involvement. It is essential for agencies to be proactive in disseminating information and demonstrating the benefits of ramp metering.

The target audience for public information dissemination should also include local leaders such as elected officials, motorists, local media, enforcement agencies, and transit authorities. It is important to reach out not only to proponents of ramp meters but also to opponents of implementation. Opponents' concerns can be addressed through ramp meter strategies, as it is often found that these concerns are products of misinformation or misunderstanding, which can be corrected.

The following public outreach techniques and tools are recommended in the FHWA *Ramp Management Handbook*:

7.1. Brochures/Flyers/Newsletters

Brochures, flyers, and/or newsletters can be mailed or hand-delivered to residents or nearby businesses, public facilities, and open house facilities near affected ramps. Information contained in the brochures may pertain to the following:

- Description of the strategies to be implemented
- Expected date and/or time of day that strategies will be in effect
- Expected benefits and cost-effectiveness of strategies
- Reasons why strategies are being implemented
- Public information and outreach activities and details
- Locations where strategies will be implemented
- Contacts or websites where additional information can be obtained or public comments can be collected
- Instructions for complying with strategies

7.2. Websites

Websites can be easily set up to provide general information about the ramp metering implementation as well as specific information about projects where ramp meters will be located. Websites can also be used to disseminate information of ramp closures if they occur during initial construction.

7.2.1. Open House Meetings

Meetings with citizens can be held before implementation of ramp meters in order to gather input and educate the public. Additional milestone meetings can be held to gather public input after implementation.

7.2.2. Inter-Agency Meetings

Meetings in the form of workshops or roundtable discussions may be held with local agencies to solicit and gather information regarding implementation of ramp strategies. This will also give agencies the opportunity to coordinate operations and activities and express their needs related to these activities.

7.2.3. Media Releases

Print media, such as newspapers, can be used to advertise ramp meter locations and implementation dates, along with times and locations of public information meetings. Departments of transportation can release statements or hold press conferences to share information with the media and answer questions. Often, graphic presentations can be prepared to strengthen understanding of ramp management strategies.

7.2.4. Signs

Public notice signs can be posted near affected ramps advising motorists of impending ramp meters. A phone number or website should be provided for motorists to obtain more information.

7.2.5. Automated Messages

Recorded automated messages can give callers the basic information pertaining to ramp meters. An option or additional phone number should be available for callers to receive more detailed information or speak with an operator.

7.3. State Marketing Strategies

7.3.1. Atlanta, Georgia

GDOT deployed more than 160 ramp meters throughout metro Atlanta between 2008 and 2010 under GDOT's "Fast Forward" program. Prior to this large ramp meter deployment, five ramp meters were deployed in 1996 and four in 2005. The 2008–2010 deployment was considered to be the public's first significant exposure to ramp meters. GDOT facilitated public outreach through a number of newspaper articles printed in the *Atlanta Journal Constitution,* and by holding presentations for community groups and neighborhood planning units. GDOT claims its outreach methods were successful, although many complaint calls were received after initial implementation. As the ramp meters were fine-tuned and drivers became adjusted to the presence of ramp meters, the number of complaint calls decreased.

7.3.2. Minneapolis/St. Paul, Minnesota

Ramp metering has been deployed in the Twin Cities since 1969; however, most of the region's 433 ramp meters were installed in the 1990s. When the ramp meters were deployed in the 1990s, the marketing and outreach campaign consisted of press releases, brochures, and radio spots using the tagline: "It's worth the wait."

7.3.3. Washington

In July 1999, Washington State developed an outreach program called “Go with the Flow” prior to implementing new ramp meters on I-405. A two-page handout extensively covered the reasons for installing ramp meters, identified the locations where they would be installed, specified when they would be installed and operational, and listed common questions and answers about ramp meters. The handout advertised the new ramp meter project as “high-tech freeways” and listed directions for using the newly installed ramp meters. Various methods of contact were also listed.

7.3.4. Louisiana

Louisiana deployed 16 ramp meters along I-12 in 2010. A two-page flyer was developed to disseminate information regarding the ramp meters. The flyer included facts about ramp meters, a map of ramp meter locations along the interstate, information about what drivers could expect, and a quote from the Department of Transportation and Development Interim Secretary: “The ramp meter system combined with the widening projects on I-12 will result in a reduction of travel times by more than 30 minutes for some commuters.”

7.3.5. Kansas City

The Kansas and Missouri DOTs jointly operate the Kansas City SCOUT Freeway Management System. About 1 year prior to ramp meter deployment, the agency began its public outreach campaign that consisted of creating an information website, videos, flyers, handouts, and fact sheets to educate the public on what to expect, how ramp meters work, how long drivers will typically wait on a ramp (about 1 minute), and how drivers will know when ramp meters are in operation. The campaign also emphasized that other cities were also using ramp meters. Additionally, public meetings were held at local large businesses and shopping centers near the affected corridor. It was found that the most effective outreach method was the information website with videos that showed ramp and freeway operation before and after ramp meters. These states indicated that once the public understood how and why ramp meters worked, the deployment was generally supported.

7.3.6. Nevada

Nevada DOT initially deployed ramp meters in 2005. To educate the community and all affected stakeholders, the Regional Transportation Commission (RTC), in cooperation with Nevada DOT and Nevada Highway Patrol, developed a communication plan that consisted of public service announcements, media and community outreach, and intergovernmental relations prior to ramp meter activation. The campaign primarily targeted commuters who used the ramps that planned to be metered. Secondary target audiences included elected officials, owners and employees of businesses adjacent to the affected ramps, local jurisdictions, media representatives, professional drivers, and municipal court judges, administrators, and staff. The campaign disseminated information in the following forms:

- Fact sheets
- Hotline
- Mobile freeway/roadway message signs
- “On the Move” television spot
- “On the Move” newsletter story
- Other jurisdictional newsletters and publications

- Call center quick glance fact sheet
- Nevada Power bill inserts
- Homeowners association newsletters

Nevada found that law enforcement officers and municipal court judges' methods to uphold enforcement were critical to the success of the ramp meter program. Nevada DOT entered into agreements with the Nevada Highway Patrol and the Las Vegas Metropolitan Police Department to pay overtime for approximately the first month as they enforced the ramp meter operation in the morning and evening peak periods. Although law enforcement personnel pulled drivers over and explained proper meter use, traffic fines were suspended during initial implementation.

7.3.7. United Kingdom

The United Kingdom Highways Agency commissioned a video to help explain the concept and benefits of ramp metering to stakeholders such as police, maintainers, operators, and local authorities. Meetings were held with stakeholders prior to implementation. Brochures were handed out to the public in the area, and news articles were broadcast on local television.

8. Ramp Meter Effectiveness

When correctly implemented, ramp meters can significantly improve performance measures such as throughput, travel time, travel speed, fuel consumption and emissions, and crash rate. Additionally, ramp meters can have a positive benefit-cost ratio. Ramp metering performance is typically evaluated through pre-deployment studies, system impact studies, benefit-cost analysis, and ongoing system monitoring and analysis.

8.1. Ramp Meter Performance Data

The following Tables 11 and 12 summarize some of the available ramp meter performance data from existing ramp meter deployments.

Table 11. Summary of Ramp Metering Performance Improvements

Performance Measure	Location and Result
Travel time	Atlanta – 10% decrease in peak period Houston – 22% decrease in peak period Arlington – 10% decrease in peak period
Travel speed	Milwaukee – 35% increase in peak period Portland –155% increase in peak period Detroit – 8% increase Los Angeles – 15 mph increase
Crash rate	Phoenix – 16% decrease during metered hours Milwaukee – 15% decrease in peak period
Crash frequency	Portland – 43% decrease Sacramento – 50% decrease Los Angeles – 20% decrease
Driver hours saved	Sacramento – 50% decrease Los Angeles – 8,470 hours per day
Vehicle volume	Milwaukee – 22% increase in peak period Sacramento – 5% increase in peak period Detroit – 14% increase in volume Los Angeles – increase of 900 vehicles per day
Gallons of fuel saved	Portland – 700 gallons per weekday
Emissions reduction	Minneapolis – reduction of 1,160 tons annually
Benefit-Cost ratio	Atlanta – about 4:1 in year 1, about 20:1 after 5 years

Table 12. GDOT Trip Travel Time in Atlanta

Corridor	Avg. Trip Time BEFORE[1]	Avg. Trip Time AFTER[1]	% Savings
I-85 N from I-285 to SR 316 (PM)	28 min.	17 min.	39%
I-85 S from SR 316 to I-285 (AM)	21 min.	16 min.	24%
I-285 N from US 78 to I-85 (AM)	9 min.	6 min.	33%
I-285 S from I-85 to US 78 (PM)	15 min.	11 min.	26%
I-75/85 N from Langford to I-20 (AM)	10 min.	6.5 min.	35%
I-75 N from I-285 to Wade Green (PM)	26.5 min.	20 min.	24%
I-75 S from Wade Green to I-285 (AM)	26 min.	21 min.	19%
I-285 N from I-20 to US 78 (AM)	14.5 min.	11 min.	24%
I-285 W from GA 400 to I-75 (PM)	13.5 min.	11.5 min.	14%
I-285 W from I-85 to GA 400 (AM)	10.5 min.	8.5 min.	19%

1. Before and after ramp meter deployment

8.2. Caltrans

Caltrans conducted an evaluation of I-580 ramp meter deployment in 2005. Caltrans strategically had set the metering rate to limit the entering volume to 405 of the before volume. The range of travel times upstream of the ramp meters on I-580 decreased as much as 55% to an increase of 40% as an attempt to discourage cut-through traffic. This strategy diverted traffic to some arterial routes. At selected ramp meters, volumes increased when ramp meters were deployed, hence the increased travel times. Overall, on the metered section, the volume increased and the travel time decreased by an average of 20% for the period of 2-7 PM and 60% for the period 4-6 PM.

8.3. Wisconsin DOT

Wisconsin DOT has conducted evaluations of ramp meters on the Madison Beltline and US 45. For the US 45 corridor, vehicle hours traveled decreased by 2%, speeds increased in the most congested section by 13%, and crash rate decreased by 21%. The Madison Beltline evaluation produced very noticeable crash reductions ranging from 50-86%. Emergency responders found the ramp meters that accident response and clearance times improved.

8.4. United Kingdom

An evaluation of the first 30 sites identified the following benefits (there are now nearly 100 sites in England):

- Flows increased by between 1% and 8%
- Downstream traffic speeds increased by between 3% and 35%
- Average travel time decreased by 13% (up to 40% at some sites)

The average ramp delay varied between 15 and 78 seconds; however, the biggest delays corresponded to the highest main freeway benefits, resulting in overall high travel-time savings.

A recent study has performed a high-level comparison of collision rates before and after installation of ramp meters in the UK and identified a 37% reduction, over and above the background trend of reduced collisions.

Table 13 summarizes the benefits from selected data in Europe.

Table 13. Europe Ramp Meter Performance Benefits

Country	Traffic Volumes	Speeds	Delays	Accidents
Germany (up to 100 sites)	n/a	Increased by >10 kph	Congestion reduced by 50%	Reduced by 40%
France (100+ sites)	Increased by 3%	Increased by 21%	Reduced by 16%	n/a
The Netherlands (50+ sites)	Increased by 0–5%	Increased by 5–30 kph	Reduced by 20%	n/a

8.5. Twin Cities, Minnesota Case Study

The ramp metering system in the Minneapolis/St. Paul region (Twin Cities) is one of the most extensive in the nation. It also has been one of the most studied systems, with more than 430 ramp meters used for corridor and regional traffic control. The Twin Cities ramp metering system was subject to an extensive evaluation in 2000 by the Minnesota State legislature because a small, but vocal, group of citizens perceived there were long delays at some ramps and thought the system operated inequitably and inefficiently. The legislature provided funding for a comprehensive independent evaluation. The ramp meters were turned off for a 6-week evaluation period. System performance data were collected for 6 weeks prior to the shutdown and then during the shutdown. Safety impacts were also analyzed by comparing the Minnesota Highway Patrol incident reporting database before and after the ramp metering shutdown.

The 2000 evaluation covered all 430 ramp meters over 210 freeway miles in the Twin Cities metropolitan area. The Twin Cities' meters were a mix of pre-timed, local traffic responsive, and system-wide ramp metering types that operated at both morning and evening peak periods. The 6-week shutdown experiment evaluated several performance measures, with highlights as follows:

- **Throughput**: Traffic volumes on the freeway mainline were observed to decrease by 9 percent when the meters were shut down. There was no appreciable change in volumes observed on the parallel arterials when the meters were shut down.
- **Travel Time**: Freeway speeds were reduced by 14 percent, or 11.9 km/h (7.4 mi/h), when the meters were shut down, resulting in greater travel times that more than offset the elimination of ramp queue delays. There was no appreciable change in the travel times on the parallel arterials observed when the meters were shut down.
- **Travel Time Reliability**: Travel times were nearly twice as unpredictable when the meters were shut down.
- **Safety**: Crashes on freeways and ramp segments increased by 26 percent when the meters were shut down.
- **Benefit-Cost Analysis**: The ramp metering system was estimated to produce approximately $40 million in benefits to the Twin Cities region. These benefits outweighed the costs of the ramp metering system by a ratio of 15:1.
- **Market Research**: Survey and focus group efforts were used to gather perceptions and opinions on the metering system. This research revealed that the majority of residents supported ramp metering and felt that the system provided them with a benefit. However, many residents also supported modifications to the system to decrease time spent waiting in the ramp queues. The research findings generally supported the observed impacts of increased safety, improved travel time, and more reliable travel times resulting from ramp meter operation. One noted discrepancy involved the time spent waiting in the ramp queues reported by travelers. Travelers perceived their wait times to be generally twice as great as the observed wait times.

The Twin Cities ramp metering evaluation experiment provided the opportunity to see the value of detailed performance measures. The observations of the experiment supported MnDOT's assertions that the system provided substantial benefits. However, the marketing research effort revealed that many residents were dissatisfied with certain operational aspects of the system, and did not necessarily understand the tradeoff between more restrictive metering and improved freeway performance. Based on these findings, MnDOT implemented modifications to achieve a better balance of the operational efficiency of the system with the perceptions of travelers, along with increased focus on public outreach to promote the benefits of the system.

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