National Research

M-0446 Ramp Metering Feasibility Study for Durham and Wake 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. It reviews ramp metering hardware, technology, site selection criteria, implementation methods, and design standards currently used by agencies that employ ramp meters. This research includes a review of the type and effectiveness of other states' marketing and outreach when implementing new ramp metering systems as well as the measures of effectiveness that ramp meters have provided to those states.

1. Ramp Meter Essentials

This section includes a brief history 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.

Currently, significant U.S. ramp metering deployments are in 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, Nevada, Kansas City, MO/KS; 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 on-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 on-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 2.2: 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

Three types of ramp metering operations are commonly used:

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

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

- One car per cycle metering – one vehicle per cycle is permitted
- Platoon metering – two to three vehicles per cycle are permitted (for use at freeway connectors or heavy ramps)

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 when mainline loops are malfunctioning or during construction.

Local Traffic Responsive

Ramp metering using local traffic-responsive operations employs vehicle detection located on the on-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 2.2, Algorithms and Coordination.) Queue management allows the ramp meter to decrease the metering rate at ramps upstream of the incident, and increase the rate at ramps downstream. This feature requires certain communications infrastructure to be installed.

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.

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.

2. Technical Research

2.1. 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 on-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.

2.1.1. 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. Often an additional status indicator light is installed on the backside of the signal pole for enforcement.

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.

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 (see Figure 1). 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")*.

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 (see photo at right). 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.

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*.

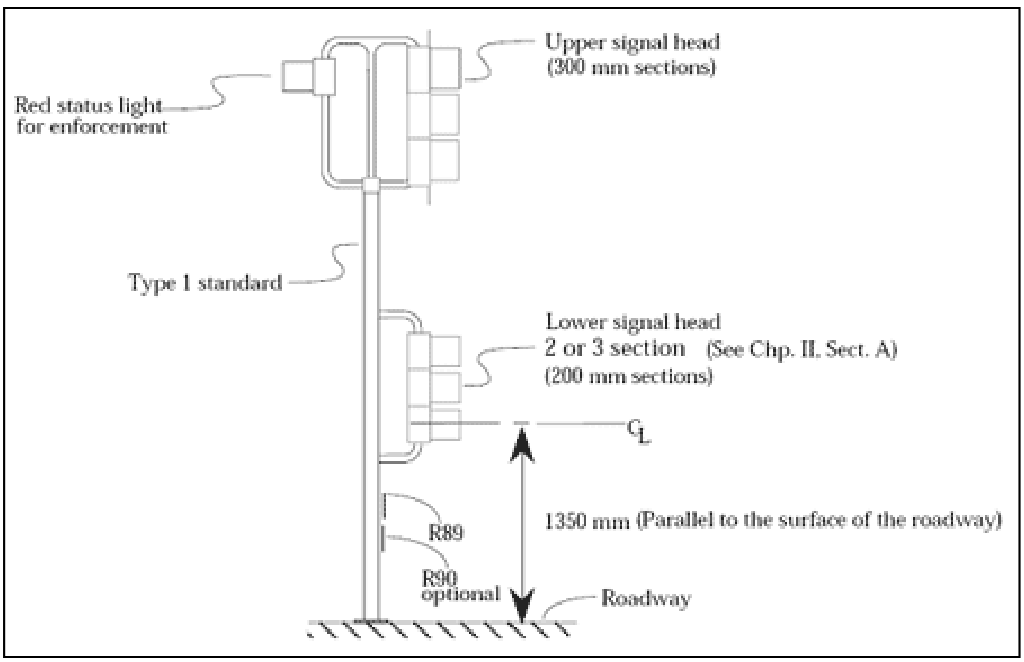
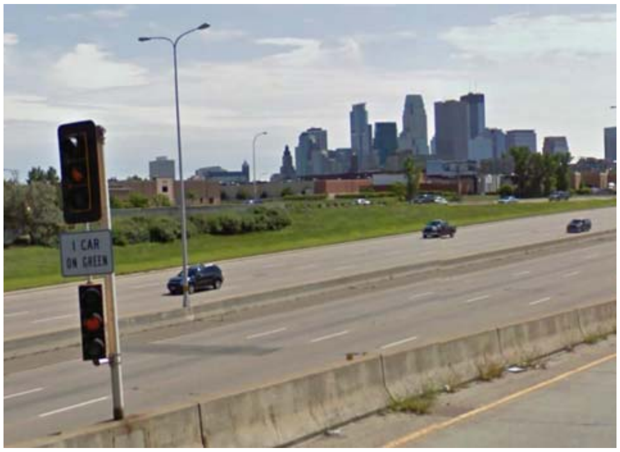


Figure 1. Typical Signal Standard used by Caltrans (NTS)

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.

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.

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 on-ramp. Each signal head has three aspects (red, amber, and green) and a yellow backing board to distinguish it from standard traffic signals.

Europe Ramp Meter Signals

- Belgium. Three aspect signal heads with yellow backing boards are used. A flashing amber signal indicates that the system has been switched off due to excessive queues. Signs on the on-ramp explain how the system works.

- Germany. Three aspect signal heads with yellow backing boards are used. The signals are switched off when not operational.
- France. Two aspect signal heads (red/amber) with a yellow backing board are used. A warning sign with a flashing amber signal installed at the ramp entry indicates when ramp metering is operational.
- The Netherlands. Three aspect signal heads with yellow backing boards are used. A warning sign with a flashing amber signal installed at the ramp entry indicates if ramp metering is operational. The lamps are switched off when not operational.

2.1.2. 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 (Figure 2). 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.

GDOT in Atlanta 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.

Southern Nevada uses inductive loop detection on ramps and radar detection on freeway mainlines to avoid hazards related to installing loops on an operating freeway. Significant CCTV coverage at ramp meter locations allows the agency to monitor ramp meter activity and control the ramp meter operations as necessary.

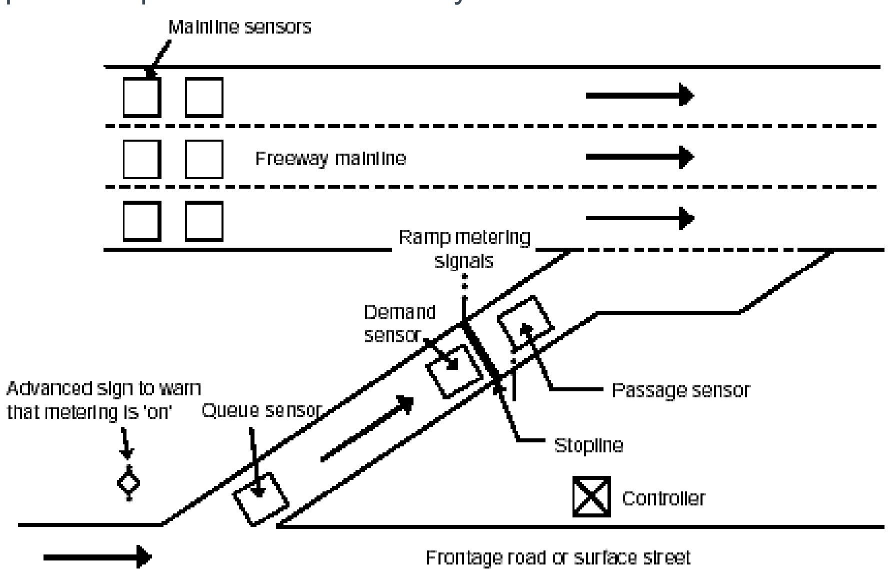


Figure 2. Conceptual Ramp Metering Detector Configurations

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 dissipate the excess before it backs up to the surface street.

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 on-ramp for queue management purposes.

2.1.3. 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.

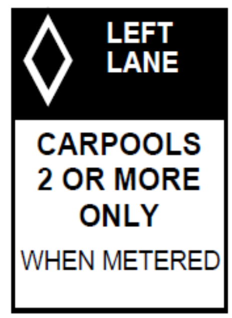
Ramp meters are controlled by traffic signal controllers operating with specialized software embedded in the controller (firmware), which differs from traffic intersection control firmware. This firmware operates the ramp metering strategies employed. Arizona uses a Model 179 controller unit that contains firmware by Bi Trans Systems developed for the Arizona Department of Transportation. Arizona requires the Model 179 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. 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.

2.1.4. 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, 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 newly 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 (Figure 3). 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. Arizona DOT also employs HOV-equipped ramp meters.

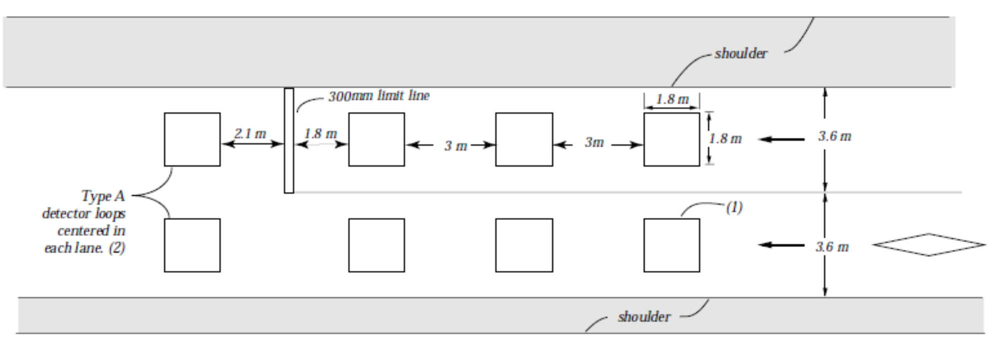


Figure 3. Caltrans diagram of two-lane ramp with non-metered HOV LANE

2.2. 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 1 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.

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.

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.

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.

Examples of Specific Algorithms

- ALINEA is a ramp metering strategy that uses local feedback. It attempts to maximize freeway mainline throughput by maintaining 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.

- 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.
- 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 ramps.

2.2.1. 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. 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 on-ramp delay, which ensures that the waiting time at on-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.

2.2.2. 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 4.2). 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.

Table 1. Summary of Ramp Meter Operation Type

Ramp Meter Operation Type	Algorithm	Vehicle Detection Required	Benefits	Downsides
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 only adjacent to 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.
Note that queue management strategies can be used with all ramp meter operation types.				

2.3. 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.

2.3.1. 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.

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.

2.3.2. 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.

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.

GDOT Ramp Meter Warrant Criteria

GDOT uses the following criteria 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 2. 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

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:

1. Freeway Volume – Vehicle flow rates of 1,200 vphpl, coupled with slow moving traffic along the freeway lanes.

2. Ramp Volume – Ramp volumes of at least 240 vph (400 vph for two lanes).

3. Speed – Multiple ramp metering case studies listed 30 mph or less as the common minimum freeway speed to warrant ramp metering.

4. 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.

5. 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.

6. 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.

7. Alternate Route – An alternative route for motorists on the arterial network to avoid delays on entrance ramps created by a ramp meter.

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. The process is summarized in Figure 4.

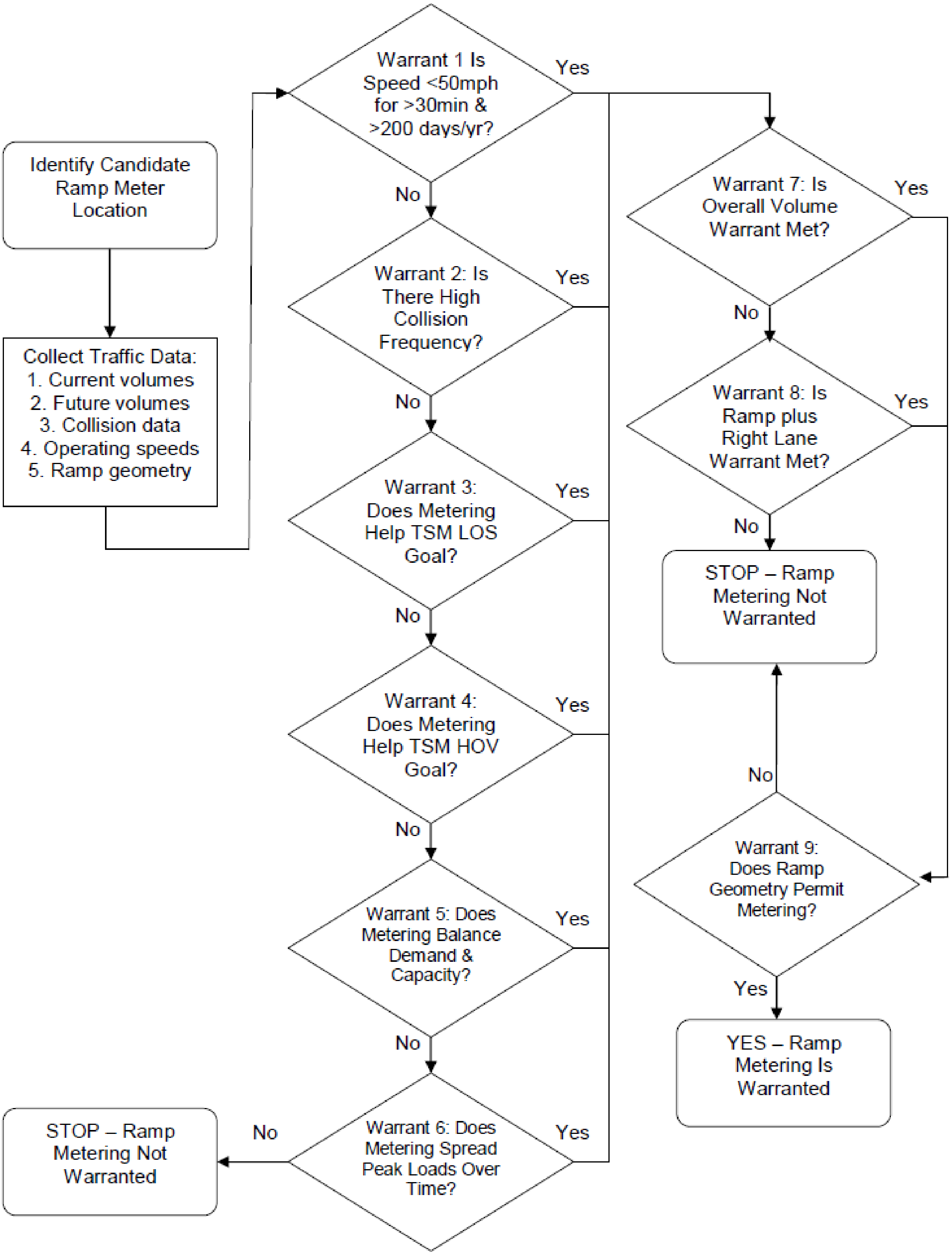


Figure 4. Arizona Ramp Metering Warrant Flowchart

2.3.3. Crash Data

Research found that other states have not used crash data as justification for ramp meter installations. Table 3 shows a summary of crash benefits for a select group of deployments in other states.

Table 3. 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%

2.4. 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.

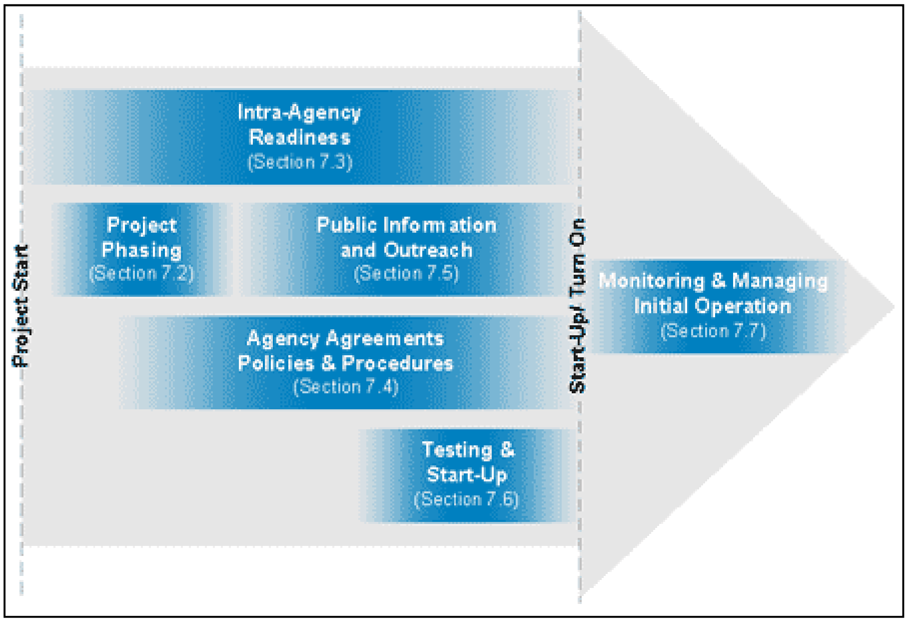


Figure 5. FHWA *Ramp Management Handbook* General Activities and Timeline for Ramp Management Strategy Implementation

2.5. Design Standards

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 procedure is found in 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

United Kingdom Highways Agency

The United Kingdom Highways Agency developed the *Ramp Metering Technical Design Guidelines* (2008) that provides extensive details of the necessary 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.

Arizona Department of Transportation—*Ramp Meter Design Guide*

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

California Department of Transportation—*Ramp Meter Design Manual*

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

Wisconsin Department of Transportation—*Ramp Metering and Control Plan*

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

2.6. Costs

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

2.6.1. Capital Costs

Capital costs include equipment such as controllers, cabinets, signal heads, and detection devices. 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.

2.6.2. 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 (Table 4).

Table 4. 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.

2.6.3. Maintenance Costs

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

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

2.6.4. 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.

3. 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*:

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

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.

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.

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.

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 release information to the media and answer questions. Often, graphic presentations can be prepared to strengthen understanding of ramp management strategies.

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.

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.

3.1. State Marketing Strategies

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.

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."

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.

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."

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.

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.

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.

4. 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.

4.1. Ramp Meter Performance Data

The following tables summarize some of the available ramp meter performance data from existing ramp meter deployments.

Table 5. 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 6. GDOT Trip Travel Time Before/After Ramp Meter Deployment in Atlanta

Corridor	Avg. Trip Time BEFORE	Avg. Trip Time AFTER	% 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%
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%

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.

Table 7. 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

4.2. 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 Mn/DOT'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, Mn/DOT 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.

Bibliography

Arizona Department of Transportation. (2003). *Ramp Meter Design, Operations, and Maintenance Guidelines*.

California Department of Transportation. (2000). *Ramp Meter Design Manual*.

Cambridge Systematics, Inc. (2002). *Mn/DOT Ramp Meter Evaluation.*

Federal Highway Administration, U.S. Department of Transportation. (2009). MUTCD.

Federal Highway Administration, U.S. Department of Transportation. (2006). *Ramp Management and Control Handbook*.

Georgia Department of Transportation. (n.d.). *Ramp Meters*. Retrieved 2012 February from Georgia Department of Transportation: http://www.dot.ga.gov/travelingingeorgia/rampmeters/Pages/default.aspx

Highways Agency (United Kingdom). (2008). Ramp Metering Technical Design Guidelines.

Levinson, L.Z. (2005). Balancing Efficiency and Equity of Ramp Meters. ASCE *Journal of Transportation Engineering*.

Mark Demidovich. (2012) Georgia Department of Transportation, Telephone interview.

Brian Hoeft. (2012) Regional Transportation Comission of Southern Nevada, Telephone interview.

Mark Sommerhauser (2012) Kansas City SCOUT, Telephone interview.

Brian Kary. (2012) Minnesota Department of Transportation, Email correspondence interview.

Minnesota Department of Transportation. (2007). Traffic Engineering Manual.

Wisconsin Department of Transportation. (2007). WisDOT Ramp Metering and Control Plan.

Other References

AASHTO, *A Policy on Geometric Design of Highways and Streets*, 2011

AASHTO. *Roadside Design Guide*, 2011

California Department of Transportation. (2001). Evaluation of On-ramp Control Algorithms.

Chris Lee, et al. (2005) Quantifying Effects of Ramp Metering on Freeway Safety Transportation Research Board.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Current Status of Ramp Metering.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Demonstration Report.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Evaluation Results.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Handbook of Ramp Metering.

European Commission. (2001). Centrico EUropean RAmp Metering Project, Ramp Metering Synthesis.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Simulation Testing.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Safety Critical Issues.

European Commission. (2002). Centrico EUropean RAmp Metering Project, Simulation Testing.

Federal Highway Administration, U.S. Department of Transportation. (2011). Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned Desk Reference: 2011 Update

Highways Agency (United Kingdom). (2008). Interim Advice Note 103/08 Advice Regarding the Assessment of Sites for Ramp Metering.

Highways Agency (United Kingdom). (2008). MCH 2471 Ramp Metering Installation Guidelines.

Highways Agency (United Kingdom). (2008). MCH 2474 Ramp Metering Operational Procedures.

Minnesota Department of Transportation. (2000) Mn/DOT Ramp Meter Evaluation, Evaluation Plan.

Minnesota Department of Transportation. (2002) Mn/DOT Ramp Meter Evaluation, Phase II Evaluation Report.

Minnesota Department of Transportation. (2002) Mn/DOT Ramp Meter Evaluation, Executive Summary.

Minnesota Department of Transportation. (2001) Mn/DOT Ramp Meter Evaluation, Final Report.

Nevada Department of Transportation. (2006) HOV/Managed Lanes and Ramp Metering Design Manual.

North Carolina Department of Transportation, *Roadway Standard Drawings*, 2012

North Carolina Department of Transportation, *Traffic Management and Signal Systems Design Manual*, 2012

North Carolina General Assembly, Statutes on the North Carolina General Assembly, , 2012

Oregon Department of Transportation. (2004) Using Archived Data to Measure Operational Benefits of ITS Investments: Ramp Meters.

Texas Department of Transportation (2004). Ramp Metering Algorithms and Approaches for Texas.

Texas Department of Transportation. (2000). Ramp Metering Design and Operations Guidelines for Texas.

Texas Department of Transportation. (2008). State of the Practice for Managed Use Lane Projects.

Virginia Department of Transportation. (1998). Ramp Metering: A Review of the Literature.

Wisconsin Department of Transportation. (2004). Evaluation of Ramp Meter Effectiveness for Wisconsin Freeways, A Milwaukee Case Study.

Zlatan Muhurdarevic, et al. (2006). Ramp Metering In Europe – State-of-Art and Beyond, Fifth International Conference on Traffic and Transportation Studies (ICTTS) Xi'an, China.

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