Ramp Metering Design

Requested by
Zhongren Wang, Division of Traffic Operations

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The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Executive Summary

Background

Caltrans is concerned with practices, policy and research related to ramp metering design:

- How best to configure storage and acceleration lanes for new on-ramps or rehabilitation projects where actual traffic counts are not yet known.
- How to optimize and balance storage length and acceleration length when existing ramps are retrofit with meters.

Answers to these questions will support Caltrans as the agency updates its Ramp Meter Design Manual and Highway Design Manual. Of central concern are ensuring that vehicles can reach sufficient merging speeds and avoiding storage queue backups into street traffic. This Preliminary Investigation sought to summarize effective practices and design solutions for metered on-ramp design.

Summary of Findings

This review of guidance documents and specifications clearly suggests that Caltrans is a leader in this area. The agency's own Ramp Meter Design Manual is a resource cited by many of the national and state guide documents and research reports that appear throughout this Preliminary Investigation.

During the course of our research, we did not uncover ramp meter design guidance exceeding the level of detail in Caltrans' own specifications or explicit findings that spelled out design solutions for new or retrofit metered ramps as specially framed in the Background section above. Nevertheless, this scan of state, national and international guidance and specifications documents, together with the synthesis of relevant research projects, touches on a number of the areas of interest to Caltrans. We also spoke with a few experts who shared some additional thoughts on this topic. Following is a summary of findings by topic area.

Expert Interviews

We spoke with two researchers from Georgia Institute of Technology:

- One researcher discussed his studies on AASHTO's standard acceleration lane values and his thoughts on their application to meter ramps.

- The other researcher discussed his current research with ramp meters and an ongoing project investigating the impacts of freeway geometric design on congestion characteristics.

National Guidance
We found relevant guidance from the states via AASHTO and NCHRP as well as at the federal level through the Federal Highway Administration (FHWA):

- AASHTO's latest edition of A Policy on Geometric Design of Highways and Streets discusses ramp metering but with limited design guidance. The minimum acceleration lane lengths used by many agencies are consistent with the values presented in this publication.
- NCHRP presents a case study that includes ramp metering in *NCHRP Report 687: Guidelines for Ramp and Interchange Spacing*.
- TRB's Highway Capacity Manual includes an example on ramp metering and its effect on demand volume.
- FHWA's Ramp Management and Control Handbook provides a number of references.

State Design Guidance and Related Research
Brief citations of California's own ramp meter design guidance and state-directed research appear in this section.

- Beyond California, this section includes detailed design information and excerpts from specifications documents from Arizona, Minnesota, Nevada, New York, Texas, Washington and Wisconsin. Also presented here are related state-sponsored research efforts.

Other State Experiences and Case Studies
Additional information about ramp metering was available for several other states. These informational web sites and case studies may provide some additional discussion of design issues.

- Information is provided for Alabama, Indiana, Georgia, Kansas/Missouri, Kentucky, Ohio and Utah.

International Guidance
We found design guidance and research from international sources.

- From Australia, ramp meter design guidance is presented for the states of Victoria and Queensland.
- New Zealand Transport Agency's standard drawings are included.
- EURAMP, the European Ramp Metering Project, features the Handbook of Ramp Metering.
- An overview of ramp metering in the Netherlands is also presented.

Additional Research by Topic
This section presents relevant research findings, grouped by topic, beyond the state-specific research presented in the State Design Guidance and Related Research section of this Preliminary Investigation.

- **Ramp Meter Design and Policy** includes two findings directly related to the central design questions raised by this Preliminary Investigation.
- Some but not all of the nine citations in **Ramp Acceleration Length and Merging** are specifically related to ramp metering, but all address the fundamental questions about acceleration and merging of interest to Caltrans.
- Two citations in **Capacity and Throughput** compare traffic demand, speed and throughput for highways with and without ramp metering.
- The topic of **Queue Management and Sensoring** is of secondary interest to Caltrans, but recent key references and a web site are presented for completeness.

Gaps in Findings

As noted earlier, Caltrans' Ramp Meter Design Manual is frequently cited throughout the literature on ramp meter design. Design guidance exceeding Caltrans' policy or based on newer research was not clearly evident.

Among the research citations presented here, some of the most relevant studies were not very recent. Research conducted by the Texas Transportation Institute, as appears in State Design Guidance and Related Research and in Additional Research by Topic (the citation Distance Requirements for Ramp Metering) are more than 10 years old. Some of the most promising findings involved researchers who were no longer active or who were unreachable.

The trend in research, particularly in recent years, appears to focus on traffic detection, control strategies, queue management and ramp network management rather than on the design characteristics and planning questions of central interest for this Preliminary Investigation.

Next Steps

The design guidance of other states may prove useful to Caltrans. An assessment of how other states specifically address design issues similarly—or differently—may help Caltrans assess where it needs a fuller understanding of the underlying issues and how it may ultimately choose to update its own Ramp Meter Design Manual. International guidance, which is less likely to be based on AASHTO specifications, may be particularly instructive.

Ramp metering remains a topic of interest to transportation researchers. Based on conversations with two researchers and considering the research methodologies described in the studies cited throughout this Preliminary Investigation, the formulation of a research project tailored to Caltrans' specific design concerns should be possible.

Contacts

During the course of this Preliminary Investigation, we spoke to or corresponded with the individuals listed below:

Georgia Institute of Technology
Michael Hunter
Associate Professor
(404) 385-1243, michael.hunter@ce.gatech.edu

Jorge Laval
Assistant Professor
(404) 894-2360, jorge.laval@ce.gatech.edu

Texas A&M University
Nadeem Chaudhary
Senior Research Engineer, Texas Transportation Institute (TTI)
Adjunct Associate Professor, Texas A&M University at Qatar
(979) 845-9890 (TTI office, Texas)
+974-6631-7558 (Qatar)
nadeem.chaudhary@qatar.tamu.edu

Expert Interviews

Informal discussions with two researchers provided background information on the topic of this Preliminary Investigation as well as possible direction for future research.

Georgia Institute of Technology

Michael Hunter

We spoke with Michael Hunter, associate professor at the School of Civil and Environmental Engineering at Georgia Tech. Hunter was co-author of two papers that address ramp design and acceleration issues:

- **"Operational Evaluation of Freeway Ramp Design,"** Michael Hunter, Randy Machemehl and Alexei Tsyganov, *Transportation Research Record*, Vol. 1751, 2001: 90-100. http://trb.metapress.com/content/f87t8v844458334m/

- **Re-Evaluation of Ramp Design Speed Criteria: Review of Practice and Data Collection Plan**, Michael Hunter and Randy Machemehl, Center for Transportation Research, University of Texas at Austin, Research Report 1732-1, April 1997. http://www.utexas.edu/research/ctr/pdf_reports/1732_1.pdf

Hunter noted that the acceleration lane lengths and taper lengths that appear in AASHTO's Green Book (see the discussion of AASHTO's A Policy on Geometric Design of Highways and Streets, 6th edition, in the National Guidance section of this Preliminary Investigation) are largely unchanged since they were established in the 1930s. One significant change was made to the 1980 edition; starting with that edition, the length of the taper no longer counted toward the length of the acceleration lane. Since a standard 50:1 taper of a 12-foot lane is 600 feet long, this change effectively added another 600 feet in required length to acceleration lanes.

Hunter said that a number of studies contemporaneous with his own indicated that the lengths in the Green Book appeared to be fairly reasonable regardless of whether the 1930s research upon which the figures were based were still justified.

By inspection, it does not appear to Hunter that all acceleration lanes retrofit with ramp meters have the distances prescribed in the Green Book, and it's arguable whether there is enough length to accelerate. It is not necessarily the case that highway traffic is slowed and merging speeds are lower during metering conditions. For example, ramp metering triggered by highway volume rather than by highway speeds may require high-speed merging.

Incident data or acceleration and deceleration profiles could be used to assess how well ramp meters are performing. Further research in this area would fall within the expertise of the Center for Transportation Operations and Safety at Georgia Tech.

Georgia Institute of Technology

Jorge Laval

At Hunter's suggestion, we also spoke with Jorge Laval, assistant professor at Georgia Tech's School of Civil and Environmental Engineering. Laval is currently engaged in a research project about the development of optimal ramp metering strategies, described at http://transportation.ce.gatech.edu/rampmeter:

> *From the web site:* This project is developing optimal ramp metering strategies using the recent advances in traffic flow theory and simulation. A recently developed theory that can explain stop-

and-go oscillations, capacity drop during congestion, and traffic dynamics under ramp metering, will be utilized to perform realistic simulations to evaluate new strategies.

The System-Wide Adaptive Ramp Metering (SWARM) algorithm will be studied and a set of ramp-metering strategies for congestion mitigation will be proposed. Although different strategies are expected to have different impacts under different traffic conditions and network configuration scenarios, the research will focus on peak demands to design the strategies. The final report will contain guidelines and the methodological steps that are required to optimize operations on a corridor and eliminate a significant portion of the recurrent congestion in the network.

In addition to this research, Laval noted that he is leading a current research project funded by the National Science Foundation that will investigate impacts of freeway geometric design—including ramps—on congestion characteristics.

Texas A&M University

Nadeem Chaudhary

We were unable to reach Nadeem Chaudhary. However, given the direct relevance of his research in this area as noted in the State Design Guidance and Related Research section of this Preliminary Investigation, the best contact information available for Chaudhary is provided in the Contacts section should Caltrans wish to try to contact him.

National Guidance

While we did not identify definitive design guidance or research at the national level, several references contained information that discussed ramp metering design and the topics of interest to Caltrans for this Preliminary Investigation.

Some of these publications cite Caltrans' Ramp Meter Design Manual as a resource on ramp meter design; this trend is consistent throughout state research findings as well. Caltrans is regarded as a leader in this area.

A Policy on Geometric Design of Highways and Streets, 6th Edition, AASHTO, 2011.
https://bookstore.transportation.org/collection_detail.aspx?ID=110
The current AASHTO publications brochure, http://downloads.transportation.org/aashto_catalog.pdf, notes that among the features of this document (commonly referred to as the "Green Book") is additional guidance on ramp metering. The Ramp Metering section that appears on pages 10-128 through 10-129 provides only general guidance, describing the operational goals, the potential benefits, the functional components, the timing and actuation methods, and selected additional citations.

Beyond this section, Table 10-3, Minimum Acceleration Lengths for Entrance Terminals with Flat Grades of Two Percent or Less, contains information cited by several states in their ramp meter designs (page 10-110). The table presents required acceleration lengths given highway design speeds and initial vehicle speeds (including 0 km/h, the stopped condition, appropriate for ramp metering). Values in this table may be modified further by Table 10-4, Speed Change Lane Adjustment Factors as a Function of Grade (page 10-111 for metric units, page 10-112 for U.S. customary units), which provides adjustments for upgrades and downgrades as great as 6 percent.

"Guidelines for Ramp and Interchange Spacing," *NCHRP Report 687*, 2011.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_687.pdf
This report provides guidelines for ramp and interchange spacing based on design, operations, safety and signing considerations. Appendix A, Scenario Based Case Studies, presents "five scenario-based case studies that demonstrate how to apply the various ramp and interchange spacing principles within the evaluation framework presented in Chapter 5" of the report. Scenario 3 includes ramp meters, and Step 1—Geometric Considerations for this scenario are presented on page 117.

Highway Capacity Manual, Transportation Research Board, 2010.
http://www.trb.org/Main/Blurbs/164718.aspx
The introduction to Chapter 22, Interchange Ramp Terminals (page 22-1), provides methodologies for "the analysis of interchanges involving freeways and surface streets," but it explicitly "does not consider the impacts of ramp metering and spillback from the freeway to the interchange."

This chapter notes further that "Chapter 34 includes supplemental examples that apply alternative tools to deal with … conditions that are beyond the scope of the procedures presented in this chapter," including "ramp metering on one of the freeway ramps connected to the interchange" (page 22-56). In this supplemental example, "the demand volumes are varied to examine the self-aggravating effects on the operation of the facility."

Ramp Management and Control Handbook, FHWA, January 2006.
http://ops.fhwa.dot.gov/publications/ramp_mgmt_handbook/manual/manual/10_1.htm

From Section 10.3.1, Design Standards:

> The design of ramp management elements should conform to the American Association of State Highway and Transportation Officials (AASHTO) standards and the FHWA's Manual on Uniform Traffic Control (MUTCD) recommendations for freeway facilities, unless deviations from these standards can be justified according to specific agency guidance and procedures. These guidelines include elements such as geometric design (horizontal and vertical curvature); cross-slopes and drainage design; signing and striping; traffic signal design and operations; and other aspects that must be addressed in the final design. Some projects may require ITS systems. State Departments of Transportation (DOT) generally have their own design standards that are provided in design manuals or other documents. Practitioners should conform to the agency-specific design guidance as well as the national standards.
>
> Many agencies use the basic implementation guidelines that are outlined in the MUTCD, while others have developed specific design standards and guidance for ramp management. One example is the Ramp Meter Design Manual from Caltrans. This document contains design criteria for storage requirements, acceleration lanes, stop bar location, and meter locations; hardware criteria for signal heads, detector loops and the controller cabinet; and information for signing and pavement markings. Another example is the WSDOT guidelines outlined in their WSDOT Design Manual, (Section 860). Additional information can also be found in WSDOT's HOV Design Guide. Agencies should consider developing their own design standards if they intend to implement ramp management to any significant scale. Agencies developing their own design standards may benefit from reviewing those developed by other agencies.

Relevant citations noted in this handbook are discussed in further detail in this Preliminary Investigation.

State Design Guidance and Related Research

Several states have detailed guidelines and specifications available related to the design and implementation of ramp metering. For some of these states, research on ramp meters is closely tied to the specifications documents. In these cases, the relevant research citations appear here rather than in the **Additional Research by Topic** section of this Preliminary Investigation.

This section includes information from California, Arizona, Minnesota, Nevada, New York, Texas, Washington and Wisconsin.

California

California ramp meter specifications and research are included here as brief citations. While these will be known to the requester and primary customers of this Preliminary Investigation, these citations may be informative to others.

Highway Design Manual, Caltrans, 2006.
http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
This manual establishes policies and procedures related to the highway design functions of Caltrans, including information about ramp metering design features.

Ramp Meter Design Manual, Caltrans, January 2000.
http://www.dot.ca.gov/hq/traffops/systemops/ramp_meter/RMDM.pdf
This manual is a comprehensive resource addressing ramp meter design and operation.

"Placement Design of Ramp Control Signals," Zhongren Wang, *Transportation Research Record*, Vol. 2023, 2007: 83-91.
http://trid.trb.org/view.aspx?id=801990
Authored by the requester of this Preliminary Investigation, this paper discusses optimization of control signal placement for ramp metering. In the Formulation and Analysis section of the report, the author discusses basic consideration for placement of the limit line itself that defines the acceleration length (downstream of the line) and the available queue storage length (upstream of the line).

Ramp Metering Design Tools and Field Test Implementation of Queue Control, Rene O. Sanchez, Gabriel Gomes, Roberto Horowitz and Pravin Varaiya, California PATH Program, University of California, Berkeley, Research Report UCB-ITS-PRR-2010-16, April 2010.
http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2010/PRR-2010-16.pdf
This research, co-funded by Caltrans, describes a ramp metering design tool that tests ramp metering systems for freeways. The Matlab-based software tool guides the user through a defined sequence of steps leading from data collection through calibration to simulation. The result of this process is a calibrated model of the freeway, which can be used to test different operational strategies, such as ramp metering. In the second part of the paper, the authors describe an innovative queue control scheme based on estimating the queue length by measuring vehicle speed and devising a proportional-integral controller to regulate the length of the queue.

Integrated Ramp Metering Design, Evaluation, and Optimization Platform with PARAMICS Simulations, CLR Analytics Inc., 2012.
http://www.clranalytics.com/resources/traffic-control
CLR Analytics describes its microsimulation applications for traffic control for Caltrans:

> This project is intended to develop an integrated ramp-metering design and evaluation platform for metering studies in Paramics. The platform has intuitive graphical interfaces in order to facilitate Caltrans practitioners. Three ramp metering systems deployed in California, including District 3, 6,

8, and 11's SDRMS, and District 7 and 12's SATMS, and District 4's TOS, were developed as Paramics plug-ins based on the hierarchical approach established at UCI ATMS testbed. With the use of the proposed platform, both Caltrans practitioners and researchers will benefit in the following aspects:

(1) Training Caltrans personnel how to properly operate aspects of the ramp-metering systems such as initializing parameters, fine-tuning of parameters, performance analysis, and hypothetical "what if" simulated testing.
(2) Designing or implementing a metering strategy to a target network.
(3) Analyzing, evaluating, and improving metering operations.
(4) Testing new metering algorithms and fine-tune parameters.

Arizona

Chapter 3, Ramp Meter Design, Ramp Meter Design, Operations, and Maintenance Guidelines, Arizona Department of Transportation, August 2003.
http://www.azdot.gov/highways/ttg/PDF/RampMeter-DesignGuide-0803.pdf
Chapter 3 (beginning on page 11 of the guidelines) includes a number of sections relevant to this Preliminary Investigation:

- Section 3.3, Choosing the Number of Lanes to Meter (page 11):

The future peak hour volume should be used to determine the number of lanes that a ramp meter requires for basic operation. Queue storage capacity is another determining factor for the number of lanes to be provided, as discussed later in this Chapter. Table 3.1 provides guidance on the number of lanes to meter based on design hour volume.

- In Section 3.4.1.2, Acceleration Distance (page 13), Arizona's required distances are consistent with general ramp guidelines that appear in AASHTO's A Policy on Geometric Design of Highways and Streets (the Green Book).

- Section 3.4.3, Design Guidelines Choosing Entrance Types (page 15):

  ADOT's established design criteria for selecting tapered versus parallel entrance types are summarized below.

  1. All new or reconstructed entrance ramps in the urban and "urban fringe" areas of metropolitan Phoenix and Tucson shall be constructed as parallel type entrance ramps.
  2. Entrance ramps in other urban areas such as Yuma and Flagstaff should be evaluated on a case by case basis for parallel or tapered type entrance design.

- Section 3.5, Design Guidelines for Placement of Stop Bars (page 15):

  This section summarizes design policies for the placement of ramp stop bars. Another term sometimes used for the stop bar is limit line.

  1. The stop bar location should be determined based on the selected transition taper, and the required acceleration length.
  2. Locate the stop bar as far down the ramp as possible in order to maximize storage capacity.
  3. Use a single 12-inch wide white line for the stop bar.
  4. Do not use staggered stop bars on multilane ramps.

- Section 3.6, Design Guidelines for Queue Storage (page 16):

  This section provides design guidelines for selecting appropriate queue storage lengths for ramp meters.

  1. The necessary storage is highly impacted by the operation of the interchange traffic signal depending on the overall traffic turning movements. If the cycle length is too long, the queues on on-ramps are likely to be longer too. Therefore, ramp meter queue storage should be coordinated with entire interchange traffic signalization.
  2. Adequate storage lengths for queues should be provided for all ramp meter installations.
  3. A two-lane storage area should be considered for ramps having a peak hour volume between 500 and 900 vph. A two-lane storage area should be provided for all ramps with peak hour volume greater than 900 vph.
  4. To minimize the impact on local street operations, ramp meter storage should be contained on the ramp whenever possible.
  5. The storage length that can be provided on the ramp itself may be limited by downstream weaving and merging distance requirements and right-of-way constraints.
  6. If the storage area cannot be provided on the ramp by widening or lengthening, improvements to the local street system near the ramp should be considered to provide the required storage.
  7. The current peak period of 5- or 15-minute arrival rates and anticipated or current ramp meter discharge rates should be used to calculate the required storage length.

- Section 3.12, Ramp Meter Retrofit Applications (page 24), presents guidelines for one-lane ramp meter to two-lane ramp meter conversion and for one-lane-plus-HOV conversion to two-lane ramp meter.

The References section of these guidelines (page 71) cites both the 1995 and 2000 editions of Caltrans' Ramp Meter Design Guidelines.

Minnesota

Chapter 3, Freeway Corridor Traffic Management, Traffic Engineering Manual, Minnesota Department of Transportation, August 2007.
http://www.dot.state.mn.us/trafficeng/publ/tem/2009/Chapter-03.pdf

- Section 3-5.03 addresses the algorithm for metered ramp control in Minnesota (page 3-7):

  Minnesota algorithm has evolved into a real-time, volume based control equation, called stratified ramp metering. Stratified metering considers traffic volumes on mainline and ramps and attempts to maximize mainline traffic volume while limiting queue waits to four minutes on local access ramps and two minutes on freeway to freeway ramps. If queue detectors sense ramps queues exceed the limits or are backing up onto local streets, the metering rates increase which clears the queue backups in the ramps.

- Section 3-5.04, Ramp Design (page 3-8), provides general design guidelines for metered freeway entrance ramps:

  1. Minimum of 300 feet between the ramp control signal and the nose (end of physical curb separation between ramp and freeway).

2. Minimum storage distance of 25 feet per vehicle for a six-minute metered volume between the cross street and the ramp control signal.
3. Two-lane ramps with single-lane entrance for all ramps with projected volumes of 500 vph or greater.
4. Adequate graded width on all ramps for future pavement widening to accommodate an HOV bypass ramp.
5. Maximum of plus one percent grade for the last 500 feet of the ramp.

Chapter 6, Interchanges and Grade Separations, Road Design Manual, Minnesota Department of Transportation, February 2001.
http://dotapp7.dot.state.mn.us/edms/download?docId=1062359

- Section 6-2.08, Metered Ramps (page 6-2(15)), discusses design alternatives for metered ramps:

  Ramps may be metered as one lane, as two metered lanes, as two metered lanes with an HOV bypass, and as two metered lanes with a metered HOV bypass. The single lane metering applies only to retrofit situations where widening of a ramp or loop is not practical, and in some cases to new construction where the Traffic Management Center decided to implement one lane metering. In all other cases, a two lane metering of the on-ramps and loops shall be designed. All the foregoing discussion of various metered combinations is for a ramp that during the off-peak periods operates as a single lane ramp. Any two lane on-ramps which are metered, and any ramp-street junctions of metered ramps which receive double left turn movements are special cases requiring a special design.

- Section 6-2.08.03, Design Details (page 6-2(16)), provides additional criteria:

  Single lane ramps and loops which will operate as two lane metered facilities should preferably have the following features in their design:

  1. The roadway portion of the ramp preceding the ramp meter should be 22 ft wide. This width will adequately provide for two lane metering and still allow for one lane operation in the off-peak periods.
  2. Rural design ramps and loops should maintain standard width shoulders in addition to the 22 ft wide pavement.
  3. A minimum of 50 ft of uniform standard 16 ft ramp width, or 18 ft in the case of widened loops, should be provided at the ramp nose when tapering out the additional metered ramp width.

- The manual also addresses HOV ramp bypass lanes and HOV bypass design criteria (page 6-2(16)).

Twin Cities Ramp Meter Evaluation, Cambridge Systematics, Inc., February 2001.
http://www.dot.state.mn.us/rampmeter/pdf/finalreport.pdf
This legally mandated study sought to document "the benefits resulting from ramp metering to traffic operations and related factors such as air quality in the Twin Cities metro region" and to demonstrate "the need for Mn/DOT to adjust its approach to ramp metering in a way that will optimize benefits while conforming to public expectation."

Nevada

Section 2.0, Metered Ramp Design, HOV/Managed Lanes and Ramp Metering Design Manual, Nevada Department of Transportation, March 2006.
http://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Planning/Safety_Engineering/2006_HOV_DesignManual.pdf

- *From Section 2.1.1, Meter and Stop Bar Location* (page 13): The location of a ramp meter and stop bar must strike a balance between available queue storage space on the ramp and acceleration distance to the freeway. The ramp meter and stop bar should be located at a position on the ramp that gives vehicles enough distance to accelerate to freeway speeds and merge safely with freeway traffic. Acceleration distance can be calculated using AASHTO standards. A minimum distance of 300 feet should be provided from the stop bar to the end of the physical separation between the metered ramp and the mainline. For loop ramps, the ramp meter and stop bar should be located near the freeway gore point, provided adequate acceleration distance is present parallel to the mainline. In either case, locating the ramp meter and stop bar further down the ramp will maximize the available storage space on a ramp. This may be particularly beneficial if restrictive metering rates are used and long vehicle queues are expected.

- *From Section 2.1.2, Number of Lanes* (page 13): The number of required lanes on a metered ramp should be based on the ramp volume, required queue storage, ramp meter release rate (either one or two vehicles allowed per green), and available ramp width. Available ramp width may be based on the existing ramp pavement or the pavement width feasible based on geometrics and topography. Shoulders may also be utilized when ramp meters are operating to increase the number of effective lanes, thereby increasing the queue storage capacity. The estimated queue and available storage distance to the upstream intersection will have an influence on the number of lanes needed. In general, the maximum discharge rate of a single metered lane is 900 vehicles per hour. This is calculated using a minimum cycle time of 4 seconds (2.5 seconds of red plus 1.5 seconds of green). The lowest practical discharge rate is 240 vehicles per hour, which is based on a 15-second cycle time. Refer to Table 2-1 for general guidelines on appropriate ramp volumes for single or dual release rates.

- Design details and drawings appear on pages 14-20 of the manual.

Ramp Meters, Nevada Department of Transportation, 2012.
http://www.nevadadot.com/Traveler_Info/Safety/Ramp_Meters.aspx
This web page provides general information to the public about the purpose and benefits of ramp meters.

New York

Chapter 24, Mobility Measures, Highway Design Manual, New York State Department of Transportation, May 4, 1998.
https://www.dot.ny.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_24.pdf
Design considerations for ramp meters are presented on pages 24-135 of the PDF. The guidelines address metering rates, including pretimed and different traffic-responsive metering strategies. The manual also addresses control of a system of ramps compared with local ramp metering (control of one or just a few ramps).

Texas

Section 6, Freeways, Roadway Design Manual, Texas Department of Transportation, May 2010.
http://onlinemanuals.txdot.gov/txdotmanuals/rdw/freeways.htm#CHDEJABH
Section 6 of this manual addresses design for ramp metering:

> **Metered Ramps**
> Where ramps are initially, or subsequently, expected to accommodate metering, the geometric design features shown in Design Criteria for Ramp Metering may be considered. Ramp metering, when properly designed and installed, has been shown to have potential benefits for the operation of the mainlanes. However, since ramp meters are installed to control the number of vehicles that are allowed to enter the mainlanes, an analysis of the entire roadway network area should be done to determine any adverse operational impacts to other roadways. It is suggested that the analysis specifically include both frontage road and adjacent cross street operations of through traffic, turning movements, and queue lengths.

Design Criteria for Ramp Metering referenced above is a publication by the Texas Transportation Institute. It is the third in a three-part report series published in 2000 by Nadeem A. Chaudhary and Carroll J. Messer of TTI. The purpose of the research was "to develop improved ramp metering design and implementation guidelines for use by TxDOT" and to "provide for more effective design, implementation, and maintenance of ramp-metering systems at existing as well as proposed freeway entrance ramps."

Related Resources:

> **Ramp Metering Technology and Practice: Tasks 1 and 2 Summary** (Part 1), Nadeem A. Chaudhary and Carroll J. Messer, Texas Transportation Institute, May 2000.
> http://tti.tamu.edu/documents/2121-1.pdf
> This report describes the researchers' study of current ramp-metering operations in Texas and other states. Both this report and Part 2 below reference the 1989 edition of Caltrans' Ramp Meter Design Manual.
>
> **Ramp-Metering Design and Operations Guidelines for Texas** (Part 2), Nadeem A. Chaudhary and Carroll J. Messer, Texas Transportation Institute, October 2000.
> http://tti.tamu.edu/documents/2121-2.pdf
> This report documents researchers' methods in developing TxDOT's roadway design manual. It includes "a review of current ramp metering practice in the United States, a review of current ramp metering practice in Texas, a review of design criteria, and the development of ramp design guidelines." The final considerations adopted by TxDOT as design criteria appear in Part 3 (below).
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> **Design Criteria for Ramp Metering: Appendix to TxDOT Roadway Design Manual** (Part 3), Nadeem A. Chaudhary and Carroll J. Messer, Texas Transportation Institute, November 2000.
> http://tti.tamu.edu/documents/2121-3.pdf
> This document "contains criteria for ramp design with explicit consideration of ramp metering" and is the actual appendix to the TxDOT Roadway Design Manual.
>
> The Design Considerations section (pages 3-6 of the report) describes considerations for determining "minimum ramp length to provide safe, efficient, and desirable operation," noting that "[t]he ability to provide sufficient storage space for ramp metering depends on the length of the ramp and the location of ramp signals."

A discussion of Figure 4, Design Issues Related to Ramp Meters, addresses distance requirements for ramp meters, including ramp storage for dual-lane ramps and considerations for placement of signal poles.

Figure 5, Clearances for Placement of Ramp Signal Posts, provides further details for post spacing for different ramp configurations (curbed and uncurbed, single-lane and dual-lane).

The Ramp Design Criteria section (pages 9-12 of the report) provides design criteria, including equations, for three ramp features:

- *Minimum stopping distance to the back of queue.* This section is based on "the basic AASHTO stopping sight distance equation."
- *Storage distance.* "Figure 6 provides the maximum queue length distribution for locating the excessive queue detector." This section also includes a "generalized spacing model … to determine single lane storage distances."
- *Distance from meter to merge.* The values presented here are based on AASHTO design criteria.

Part 2 of this report contains additional supporting calculations and discussions for the final criteria presented in Part 3.

Washington

Ramp Meters, Washington State Department of Transportation, 2012.
http://www.wsdot.wa.gov/Traffic/Congestion/rampmeters/
This web page answers general questions for the public about ramp meters.

Chapter 1360, Interchanges, Design Manual, Washington State Department of Transportation, July 2011.
http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/1360.pdf
From Section 1360.05(7), Ramps—Ramp Meters (page 1360-10):

> Ramp meters are used to allow a measured or regulated amount of traffic to enter the freeway. When operating in the "measured" mode, they release traffic at a measured rate to keep downstream demand below capacity and improve system travel times. In the "regulated" mode, they break up platoons of vehicles that occur naturally or result from nearby traffic signals. Even when operating at near capacity, a freeway main line can accommodate merging vehicles one or two at a time, while groups of vehicles will cause main line flow to break down.
>
> The location of the ramp meter is a balance between the storage and acceleration criteria. Locate the ramp meter to maximize the available storage and so that the acceleration lane length, from a stop to the freeway main line design speed, is available from the stop bar to the merging point. With justification, the average main line running speed during the hours of meter operation may be used for the highway design speed to determine the minimum acceleration lane length from the ramp meter. (See 1360.06(4) for information on the design of on-connection acceleration lanes and Chapter 1050 for additional information on the design of ramp meters.)
>
> Driver compliance with the signal is required for the ramp meter to have the desired results. Consider enforcement areas with metered ramps.
>
> Consider HOV bypass lanes with ramp meters. (See Chapter 1410 for design data for ramp meter bypass lanes.)

The reference to design of on-connection acceleration lanes refers to tables consistent with AASHTO's Green Book for general design of acceleration lane length based on initial speed and desired merging speed.

Related Resource:

> **Chapter 1050, Intelligent Transportation Systems**, Design Manual, Washington State Department of Transportation, July 2011.
> http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/1050.pdf
> This chapter describes the systems engineering process for implementing complex technology projects. It does not include design specifications.

Wisconsin

Chapter 2, Ramp Metering, Intelligent Transportation Systems (ITS) Design Manual, Wisconsin Department of Transportation, 2004.
http://www.topslab.wisc.edu/resources/its/ITSDM_Chapters_1-7.pdf

- Section 2.1, Basic Ramp Meter Types (page 2-1), provides recommendations, typical uses and appropriate ramp volumes for six types of metered ramp:
  - SOV—single-lane ramp meter, termed single occupant vehicle.
  - SOV/HOV—dual-lane ramp meter including high-occupant vehicle priority treatment.
  - 2 SOV—dual-lane ramp meter with no HOV priority treatment.
  - 2 SOV/HOV—three-lane ramp meter including HOV priority treatment.
  - System to System Ramp Meters—a special classification of ramp meter requiring additional considerations due to the unique nature of freeway system interchanges.
  - Temporary Ramp Meters—used for ramps under construction, or ramps that only need ramp metering for a short period of time.

- Section 2.3, Ramp Meter Design Process (page 2-3), provides 15 steps "to ensure successful implementation and proper operational capabilities."

- Section 2.6, Geometric Considerations (page 2-7) states that "[g]eometric requirements for metered ramps depend upon several factors, including:
  - *Peak hour volume*, which affects the storage length and width of the ramp.
  - *Percentage of high-occupancy vehicles (HOVs)*, if available, or *local trip generators* for the ramp which affects ramp width when considering installation of an HOV lane.
  - *Design speed* of the mainline for the ramp under consideration, which affects the acceleration distance after the stop bar (acceleration distances per AASHTO's A Policy on Geometric Design of Highways and Streets, latest edition).
  - *Right-of-way availability*, which will factor into the length and width of the ramp.
  - *Enforceability* of the ramp, which will determine whether an enforcement zone is desired for the ramp meter (whether an HOV lane is present or not).
  - *Construction funding*, which may influence the extent to which the ramp can be modified, affecting ramp width, length, acceleration lanes and HOV treatment and enforcement.

  Figure 2-2 provides recommended and minimum widths for ramp meters based on configuration type.

- Sections 2.6.1 through 2.6.4 provide additional guidance on ramp taper ratios and other considerations for different types of ramps.

- Figures 2-3 through 2-8 (pages 2-9 through 2-14) are detailed design drawings for different types of metered ramps.

- Section 2.7, Ramp Meter Stopbar/Signal Placement (page 2-15) addresses the issue of primary concern to Caltrans:

> Ramp meter stop bar placement revolves around the following fundamental issues:
> - Ramp acceleration required.
> - Ramp storage required.
> - Stop bar signal sight distances.
>
> Once the acceleration and storage distance requirements have been established (from the *initial data collection* and *determination of ramp meter type*), the placement of the stop bar can be determined. If the ramp is being widened or lengthened, the stop bar placement must also be determined side-by-side with the geometric design of the ramp. For sight distance, the most desirable location for a stop bar is at the end of a tangent section of the ramp. For loop ramps, the stop bar placement typically should be near the freeway gore, provided adequate acceleration distance is present parallel to the mainline.
>
> While ramp acceleration distances are known entities based on AASHTO Policy on Geometric Design of Highways and Streets, the storage distance can also be affected by the operational intent of the ramp meter. If a very restrictive metering rate is desired for a location, the storage distance requirement may be longer than the minimum established under *Determination of Ramp Meter Type*. **Under any circumstance, the placement of the stop bar for ramp meters must be reviewed by the Freeway Operations Unit prior to proceeding with final design and layout of the ramp.**
>
> When the use of [an] overhead sign support (mastarm) becomes necessary, such as a nonseparated 2 SOV / HOV ramp meter, placement of the overhead signals should be over the two single occupant vehicle lanes, with the side-mounted Type 2 signal assembly placed at the HOV lane. Only under the most restrictive geometric constraints should the overhead signals be placed over one SOV lane and the HOV lane.

(Note: The above information on ramp meters is updated in Chapter 5, Ramp Meters, of WisDOT's October 2009 publication Intelligent Transportation Systems Design & Operations Guide. Please contact WisDOT [http://www.dot.wisconsin.gov/] for access to this password-protected file. WisDOT's Transportation System Development—Bureau of Highway Operations, Traffic Engineering Section, maintains the guide.)

Wisconsin Statewide Ramp Control Plan: WisDOT Ramp Metering and Control Plan, Wilbur Smith Associates, July 2006.
http://www.topslab.wisc.edu/its/rampmetering/WisDOT_ramp_control_plan.pdf
The purpose of this document was "to lead the development of an institutional and procedural plan for integrating the implementation criteria for ramp control strategies into statewide planning and programming processes."

Geometric considerations are addressed on page 13 of the report:

> A number of states have design guidelines accounting for geometric considerations for metered entrance ramps. Common amongst the designs are certain characteristics that make ramps suitable for metering. The three primary considerations are the availability of storage space, adequate acceleration distance and merge area beyond the meter, and sight distance.

Ramp storage requirements can depend on ramp demand volumes and metered rates, ramp entry flow patterns (e.g., platoons caused by adjacent upstream signals), and availability of surface street storage. The availability of adequate vehicle storage can often be addressed by using two or more lanes along the ramp. This can be accomplished by restriping or reconstructing ramps to allow for two or more lanes. Our literature review revealed that consensus has not yet been reached on the most appropriate way to release vehicles from multiple lane ramps. Currently it is possible to find jurisdictions releasing vehicles simultaneously, intentionally staggered, and independently (randomly). As noted in the 1995 update of Ramp Metering Status in North America, one loop ramp in Minneapolis was widened to four lanes approaching the ramp meters. The meters release vehicles from two lanes at a time, alternating between the right pair and the left pair. Downstream of the meter the vehicles merge into one lane before reaching the freeway. Northern Virginia and Seattle are two systems that release vehicles simultaneously, while Chicago releases vehicles one at a time.

The third consideration is sight distance. Because of the curvature on many ramps, it is difficult to obtain minimum stopping sight distance requirements. Additionally, unless the public is well informed, drivers generally are not expecting to stop on an entrance ramp. Therefore, advance warning signs are usually needed to make drivers aware of the forthcoming stop. Blank out signs or static signs enhanced with flashing lights are the most common forms used. In addition to advance signing, at high accident ramps, INFORM (Long Island, New York) also uses strobe lights in the red lens to help emphasize the stop indication. Many states have standardized advance warning signs and other ramp metering considerations.

Additional geometric considerations include:

- Ramp Width—If more than one metering lane is desired, adequate width is required for side by side (tandem) metering and/or preferential HOV bypass lanes.
- Grade—Ramp grades should not be restrictive during adverse weather or for certain types of heavy vehicles.
- Merge Area—The present design should facilitate a smooth merge for vehicles accelerating after being stopped at the meter.

Evaluation of Ramp Meter Effectiveness for Wisconsin Freeways: A Milwaukee Case Study, Wisconsin Department of Transportation Council on Research, October 2004.
http://wisdotresearch.wi.gov/wp-content/uploads/45-17rampmeters.pdf
One of the purposes of this research funded by WisDOT research was to determine underlying relationships that permit evaluation of new ramp meters or ramp meter systems elsewhere. The report discusses the use of computer modeling programs for assessing the effect of alternative geometric configurations. The software simulation packages used were Paramics, Dynasmart-P and QRS II. Geometric modeling is described on page 72 of the report:

Geometry and Controls: Paramics allows a wide variety of road geometries, vehicle restrictions and intersection controls to be placed on the network, including detector locations. Paramics does not provide for a large array of ITS elements. However, Paramics can create random incidents and evaluate the performance of the traffic systems with such incidents. Paramics also has the capacity to simulate the effects of variable message signs, provided that the user specifies a set of compliance rules. Unlike some other microsimulation packages, Paramics can handle very large arterial networks.

Other State Experiences and Case Studies

This section includes information about ramp meters from the following states where specific design guidance was not available: Alabama, Georgia, Indiana, Kansas/Missouri, Kentucky, Ohio and Utah. It is not an exhaustive summary of ramp metering deployments in the United States but it does present further sampling of practices and efforts to evaluate ramp metering.

Alabama

Applications of Freeway Ramp Metering in Alabama, Virginia P. Sisiopiku, Anirban Das and Andrew Sullivan, University Transportation Center for Alabama, UTCA Report 04203, March 2005.
http://ntl.bts.gov/lib/24000/24900/24919/04203fnl.pdf
This project assessed the applicability of various ramp metering strategies to congested freeway segments in Alabama. As noted on page 29 of the report:

> A case study was performed with simulation modeling to determine the effects of ramp metering on Interstate corridors in the Birmingham region. The micro simulation tool CORSIM was chosen for this purpose.

Modeling techniques may be of interest to Caltrans in development of new ramp meter installations. This report's list of references includes the 2000 edition of Caltrans' Ramp Meter Design Manual.

Georgia

Ramp Meters, Georgia Department of Transportation, 2010.
http://www.dot.ga.gov/travelingingeorgia/rampmeters/Pages/default.aspx
This web page provides general information about ramp meters to the public. It also features a Location & Schedules page for ramp meters throughout Georgia.

GDOT Design Policy Manual, Georgia Department of Transportation, December 16, 2011.
www.dot.ga.gov/doingbusiness/PoliciesManuals/roads/DesignPolicy/GDOT-DPM-Chap13.pdf
While this manual does not provide specific design guidance, it states that ramp metering has impact on demand (page 13-17):

> The presence of ramp metering affects freeway demand and must be taken into consideration in analyzing a freeway facility.

Fast Forward: Ramp Meter Design for Metro Atlanta, Taylor H. Stukes, Gresham, Smith and Partners, undated.
http://www.itsga.org/2006_annual_meeting/presentations/2Session/1GDOT_Ramp_Meters.ppt
Primary design criteria for the deployment of Atlanta ramp meters are presented on slide 7 of this PowerPoint presentation. The criteria include:

- Stop bar location.
  - Provide minimum AASHTO acceleration length for posted speed.
  - Provide maximum vehicle storage.
  - Provide physical separation from mainline to prevent cheating.
- Two-lane ramp or single-lane ramp?
  - Travel lanes: 12 feet wide.
  - Inside shoulder: 4 feet wide.
  - Outside shoulder: 10 feet wide.
  - *Or obtain FHWA design exception.*

Among the Suggestions for Next Time (slide 13):

- Evaluate ramp capacity and queue storage prior to design phase of project, and widen/lengthen ramps to accommodate longer queues.
- Establish design criteria to ensure consistent design (easier to build and easier to maintain).
- Involve all departments of DOT during planning phase (roadway, traffic, construction, maintenance).

Indiana

Ramp Metering and High Occupancy Vehicle Facilities: A Synthesis Study, Abhishek Bhargava, Euridice Oware, Samuel Labi, Kumares C. Sinha, Purdue University, Project No. C-36-17PPP, 2006.
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1752&context=jtrp
From the abstract: The study was carried out in response to a need stated by INDOT to investigate the effectiveness of high occupancy vehicle lanes and ramp metering as congestion mitigation strategies in the state of Indiana. A synthesis study was performed to provide a comprehensive review of the components, effectiveness, costs and implementation considerations of these techniques. The states using these strategies were identified and a detailed study of the state of the art and state of the practice was done. The findings from the synthesis study were used to develop a set of guidelines that may be followed for the implementation of these facilities. The study also included a feasibility analysis of these facilities on the I-70 freeway in Indianapolis, between I-65 and I-465.

Kansas/Missouri

"Ramp Metering Delivers–Again," Jason Sims, *ITS International*, Vol. 17, No. 3, May-June 2011: 24-25.
http://trid.trb.org/view/2011/C/1107683
From the abstract: Kansas City Scout, a partnership between the Missouri and Kansas Departments of Transportation that provides an intelligent transportation system for the greater Kansas City Area, activated the first ramp metering system in the region [in 2010]. The ramp metering project was a retrofit low-cost project to deliver accident reduction engineering principles of ramp metering. KC Scout implemented a corridor adaptive approach to controlling the ramp signals with Corridor Adaptive Ramp Metering Algorithm (CARMA), an innovative software system. This means that the meters are part of a smart system that allows them to be activated based on traffic demand, but also specifically during the morning and afternoon rush hour periods. The project had three primary goals: to decrease the number of sudden weaving and braking incidents that happen as vehicles merge onto the freeway; reduce accidents and allow more vehicles to smoothly drive along the freeway; and allow more cars to use the freeway.

Kentucky

Ramp Meters, Kentucky Transportation Cabinet, 2011.
http://transportation.ky.gov/Congestion-Toolbox/Pages/Ramp-Meters.aspx
This web page provides information about the benefits of ramp meters and includes several related references, including Caltrans' Ramp Meter Design Manual.

Ohio

I-74 Ramp Metering Study, HNTB, August 2004.
http://transportation.ky.gov/Congestion-Toolbox/Documents/I-74%20Ramp%20Metering%20Study.pdf
This report summarizes the impact of ramp meters on traffic flow along Interstate 84 in Hamilton County, Ohio. Section IV, Traffic Modeling (page 8), addresses corridor modeling and the software that "utilizes a variety of inputs from pavement type, curve radii, grade changes, car following characteristics, and origin-destination data to replicate existing and future roadway conditions."

Utah

Why Do They Stop Traffic Before It Gets on the Freeway? John Haigwood, Utah Department of Transportation, 2010 Utah DOT Engineering Conference, 2010.
http://www.udot.utah.gov/main/uconowner.gf?n=16932307331236902 (conference agenda)
The presentation describes ramp metering in Utah, including a brief history, benefits, state and national statistics, and a discussion of the interconnection of ramp meter design and desired operation.

International Guidance

This section provides ramp meter design guidance from two states in Australia, the New Zealand Transport Agency and the European Ramp Metering Project. Also included is an overview of ramp metering in the Netherlands.

Australia

Managed Freeways: Freeway Ramp Signals Handbook, VicRoads, November 2010.
http://www.vicroads.vic.gov.au/Home/Moreinfoandservices/RoadManagementAndDesign/DesignStandardsManualsNotes/ManagedFreewayManuals/FreewayRampSignalsHandbook.htm
This handbook is the primary reference for planning, designing and operating freeway entry ramp signals in the state of Victoria. Chapter 6, Design of Ramp Signal Installations (http://www.vicroads.vic.gov.au/NR/rdonlyres/ED9EE8EE-999D-47B9-8B53-623511C198DC/0/Chap6_FreewayRampSignalsHandbk_LoRes.pdf), addresses the topics of primary concern to this investigation:

- Section 6.1, Overview of the Design Process (page 58 of the publication), describes VicRoads' two-phase design approach:

  Phase 1, Capacity analysis and storage design
  - Design traffic flows.
  - Number of lanes at the stop line.
  - Storage requirements.

  Phase 2, Design plan: geometry and devices
  - Number of lanes.
  - Stop line location.
  - Storage design.
  - Distance for acceleration and merging.
  - Traffic management devices.

The chapter addresses each of the steps in both phases in considerable detail. Discussions of interest to Caltrans are noted below:

- Section 6.3, Capacity Analysis and Storage Design (page 59), includes separate considerations for "upgrading of an existing freeway or a new ramp/freeway" and for "existing freeway" ramps.

- Section 6.3.3, Number of Traffic Lanes at the Stop Line (page 62), includes calculations and a detailed graphic (Table 6.1, page 63) displaying ramp storage and cycle time for a number of different ramp designs.

- Section 6.3.4, Ramp Storage Requirements (page 65), details the "desirable standard" and also addresses storage difficulties.

- Section 6.4, Geometric Design and Layout of Devices (page 68), includes a discussion of stop line location and six standard drawings for different metered ramp configurations. Discussions of entry ramp designs in this section include considerations for acceleration length and special considerations for trucks, high-occupancy vehicles and transit vehicles.

Chapter 9, Intelligent Transport Systems, Road Planning and Design Manual, State of Queensland, Australia, June 2009.
http://www.tmr.qld.gov.au/~/media/94327e24-69a0-4276-9b89-0985a52da1a5/rpdm_chapter19.pdf
Ramp metering systems are addressed on page 26 of the manual. The following design considerations, among others, are noted on page 28 without providing further guidance in the chapter:

- Ramp nose locations and ramp radii which provide sufficient acceleration distance from a future stop bar and ultimately a safe transition to the mainline traffic flow.

- Sufficient queue length storage upstream of the stop bar to keep arterial roads clear and un-congested.

Europe

EURAMP Handbook of Ramp Metering, Deliverable D7.5, European Community, September 2007.
http://www2.napier.ac.uk/euramp/dels_forweb/D7.5%20Handbook%20of%20Ramp%20Metering.pdf
From the web site of the European Ramp Metering Project (http://www2.napier.ac.uk/euramp)*:* The major objective of the EURAMP project is to advance, promote and harmonize ramp metering control measures in European motorways in the aim of improving safety and increasing efficiency of traffic flow. This major objective is pursued within EURAMP via a number of multifaceted actions and sub-objectives:

- Advancement of methodological issues, with particular focus on traffic flow safety, to secure a European technological leadership in the area.
- Consolidation, harmonization and advancement of ramp metering practice in Europe.
- Demonstration of new developments in European sites and paving the way for a new generation of extended (network-wide) ramp metering installations.
- Co-operation of ramp metering with signal control and further heterogeneous control measures for maximum synergy in terms of traffic flow efficiency and safety.

For this Preliminary Investigation, the most relevant of the EURAMP deliverables (http://www2.napier.ac.uk/euramp//eu_dels.htm) is the EURAMP Handbook of Ramp Metering. Since it deals with specific and varying design requirements of a number of governments, it does not present specific geometric design guidance for ramp meter design or placement. Further, as noted, on page 49 of the handbook:

> In some countries, ramp metering is not allowed to become active until the mainstream mean speed falls below a certain threshold, on the grounds that metered vehicles, having to accelerate from standstill, may have too low a speed when merging into the mainstream, which may affect merging safety.

Several topics throughout the manual address the central issues of this Preliminary Investigation. Section 2.7.3, Limited Ramp Storage (page 16) addresses ramp storage issues and solutions:

As urban ramp layouts were not originally designed to store vehicles for control purposes, the available storage space may allow for storage of some 10-50 vehicles per ramp (according to the ramp length/width) which may be insufficient to fully protect the mainstream from overload if the ramps are not sufficiently spacious. If the available ramp storage space is not sufficient, the obtained ramp metering benefits will be less than the maximum achievable.

This fact suggests that, for maximum exploitation of the potential ramp metering benefits, the following should be considered:

(i) Storage space on metering ramps could be increased via appropriate (re-)design of the ramp layout (e.g. widening of the ramp).

(ii) In cases of high arriving mainstream flow q_{in}, the ramp overflow could be avoided or retarded via appropriate linking (coordination) of control actions at several ramps (section 3.6).

(iii) If most ordinary urban ramps are relatively short, the metering of motorway-to-motorway ramps (if any), which are frequently longer and wider than ordinary ramps, is strongly recommended.

(iv) In some cases it may be possible to extend the ramp queue in an orderly way (i.e., without hindering traffic not bound for the on-ramp) within the adjacent urban streets which may call for appropriate re-design of the adjacent urban intersection and suitable urban signal control actions. For example, Figure 2-8 illustrates a possibility of storing vehicles on the straight, left turning and right turning lanes (bound for the on-ramp) at the adjacent street intersection upstream of the on-ramp so as to enlarge the available ramp storage space for ramp metering. It should be emphasized that, in this case, the ramp queue management procedures and techniques presented in section 3.5 should be appropriately extended to consider the enlarged available storage space.

Other topics of possible interest to Caltrans include:

- Section 3.2, Uncertainty of Flow Capacity (page 19).
- Section 3.5.2, Ramp Queue Estimation (page 27).
- Section 3.5.3, Ramp Queue Control (page 30).

Netherlands

Ramp Metering in the Netherlands: An Overview, Frans Middelham and Henk Taale, AVV Transport Research Centre, The Netherlands, 2006.
http://frans.middelham.nl/Pdf/264_Middelham_add25429.pdf
This overview article describes ramp metering in the Netherlands. It briefly addresses design aspects (page 2) and focuses on metering algorithms and effects of metering.

New Zealand

Ramp Meter System Standard Drawings, New Zealand Transport Agency, Document No. ITS-05-03, September 2011.
http://www.nzta.govt.nz/resources/intelligent-transport-systems-05-03/docs/its-05-03.pdf
This document presents ramp meter system standard drawings for New Zealand. Section 1.0, Ramp meter system layout drawings (page 1), shows five detailed drawings:

- Standard ramp metered entrance details. Included on this drawing are additional information and tables about design criteria, entrance type, ramp meter location along ramp and ramp storage needs. This figure is reproduced as Appendix A to this Preliminary Investigation.
- Two lanes metered—side mount option.
- Two lanes metered—gantry option.
- Two lanes metered plus bypass.
- Motorway to motorway meter locations.

Additional Research by Topic

This section addresses research beyond the state-specific studies noted earlier in this Preliminary Investigation. It is grouped into four areas:

- **Ramp Meter Design and Policy** includes findings most directly relevant to the questions in this Preliminary Investigation.
- The areas of **Ramp Acceleration Length and Merging** and **Capacity and Throughput** address central questions related to ramp meter design.
- **Queue Management and Sensoring** is of secondary interest to Caltrans for this Preliminary Investigation but is included for completeness.

Ramp Meter Design and Policy

"Freeway On-Ramp Design Criteria for Ramp Meters with Excessive Queue Detectors," Nadeem A. Chaudhary and Carroll J. Messer, *Transportation Research Record*, Vol. 1796, 2002: 80-85.
http://trb.metapress.com/content/u240t44u3602k584/
From the abstract: Guidelines were developed for designing freeway on-ramps in which ramp metering is envisioned. More specifically, design issues were probed for ramps in which the ramp meter utilizes a queue detector to identify and prevent a queue of vehicles from blocking the upstream intersection. First, the benefits of ramp metering operation were delineated, and general design considerations were then drawn up. Finally, design criteria were developed for three distance requirements for freeway on-ramps: safe stopping distance, storage distance, and acceleration distance.

These findings are related to the Texas research discussed in the **State Design Guidance and Related Research** section of this Preliminary Investigation.

Distance Requirements for Ramp Metering, Sameer Sharma and Carrroll J. Messer, Texas Transportation Institute, November 1994.
http://tti.tamu.edu/documents/1392-5.pdf
From the abstract: A methodology for determining the optimal placement of the ramp meter signal has been presented. Guidelines for effecting a trade-off between queue storage and freeway merging distance requirements have also been presented. A sample problem demonstrates the use of the presented methodology.

Although is an older publication, the methodologies presented throughout this paper appear to remain relevant to this Preliminary Investigation.

Ramp Acceleration Length and Merging

"Microsimulation Model for Motorway Merges with Ramp-Metering Controls," J. Al-Obaedi and S. Yousif, *IEEE Transactions on Intelligent Transportation Systems*, Vol. PP, No. 99, October 2011: 1-11.
http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=6060913
From the abstract: This paper presents a newly developed microsimulation model for motorway merge traffic, focusing on issues that relate to ramp-metering control and its effectiveness. The model deals with general and more specific drivers' behavioral tasks, such as the drivers' cooperative nature in allowing other drivers to merge in front of them either by decelerating or shifting to adjacent lanes. Compared with the S-PARAMICS software, using the same data, the model showed better results. The effectiveness of some of the widely used RM control algorithms, such as Demand-Capacity, ALINEA, and ANCONA, were also assessed after finding the optimum parameters (such as critical occupancy and position of loop detectors).

“Driver Behavior at Freeway-Ramp Merging Areas,” Alexandra Kondyli and Lily Elefteriadou, *Transportation Research Record*, Vol. 2124, 2009: 157-166.
http://trb.metapress.com/content/t080h6h045564754/
From the abstract: This study conducted three focus groups to investigate drivers’ intended actions along a freeway-ramp merging segment. Several scenarios were discussed in which participants indicated their thinking process and likely actions while merging or traversing a merging segment. The study considers noncongested and congested traffic conditions. It also correlates the drivers’ responses to their individual characteristics.

“Evaluation of Effects of Ramp Metering on Merging Operations,” Pengjun Zheng and Mike McDonald, *Transportation Research Record*, Vol. 2012, 2007: 105-112.
http://trb.metapress.com/content/23765uhx06481013/
From the abstract: Little research has been done to investigate the possible effects of ramp metering on the merging operation. The research described in this paper focuses on the comparisons of merging operations under both metered and unmetered scenarios. Time-series data of the merging process were collected using the TRG instrumented vehicle and video cameras at a tapered motorway merge site. The data included accurate vehicle speed measured by laser speedometer, leading and following headway measured by radar, driver’s eye movement derived from in-car camera, etc. Following a comprehensive analysis of the data, it was found that merging operations under ramp control could be significantly different from free-merging. Merging maneuvers may become more difficult as a result of ramp control. The equity implications of such effects are discussed. It is believed that the understanding gained from this research will be useful for the design and operation of ramp metering.

“Observed Distribution Patterns of On-Ramp Merge Lengths on Urban Freeways,” Hanwen Yi and Thomas E. Mulinazzi, *Transportation Research Record*, Vol. 2023, 2007: 120-129.
http://trid.trb.org/view/849747
From the abstract: Three on-ramp sites with moderate to high volumes of through and merge traffic along I-35 within the greater Kansas City, Kansas and Missouri, metropolitan area were selected for investigation of the distribution patterns of the merge lengths of ramp vehicles. Merge vehicles were categorized into three types: free merge, challenged merge and platoon merge. The potential applications of these findings [are] discussed, with an example illustrating how to use the 85th-percentile merge length to determine the minimum merge lane length for an urban freeway on-ramp.

“Potential Updates to 2004 Green Book’s Acceleration Lengths for Entrance Terminals,” Kay Fitzpatrick and Karl Zimmerman, *Transportation Research Record*, Vol. 2023, 2007: 130-139.
http://trb.metapress.com/content/g71u69823x07xw36/
From the abstract: Findings from recent studies were compared with the existing Green Book values and the calculated suggested acceleration lengths. The suggested lengths determined in this paper, which are based on more realistic speed assumptions, more current acceleration lengths, and findings from recent research, are longer than the values in the Green Book. The paper recommends that additional research be done on acceleration lengths to determine whether the Green Book values should be increased.

“Operational Evaluation of Freeway Ramp Design,” Michael Hunter, Randy Machemehl and Alexei Tsyganov, *Transportation Research Record*, Vol. 1751, 2001: 90-100.
http://trb.metapress.com/content/f87t8v844458334m/
From the abstract: Freeway entry ramp design speed criteria were evaluated by observing six (nonloop) ramps in three Texas cities. Performance characteristics for numerous ramp features and volume combinations were compared. First, for virtually all observations, ramp driver speeds were found to be greater than 50 percent of the freeway design speed; therefore, a 50th percentile design speed might have negative safety implications. Second, the ability of entry ramp drivers to see freeway right-lane traffic, into which merging is intended, before reaching the ramp gore was found to be very important. Therefore, the AASHTO acceleration lane length measurement model for taper-type ramps should be clarified. The

acceleration lane should be considered to begin only when ramp drivers have an unobstructed view of freeway right-lane traffic.

"Theoretical Study on Design of Acceleration Lane for Expressway," L. I. Shuo, *Journal of Highway and Transportation Research and Development*, Vol. 15, No. 4, Dec. 1998: 52-56.
http://trid.trb.org/view/1998/C/492135
From the abstract: This paper presents a new design method for acceleration lane in which the traffic volumes on main line of expressway and on-ramp are considered in the computing of the acceleration lane length. A group of computer simulated design lengths of acceleration lane are also provided for the purpose of comparison between varied methods and the traditional design standards. Finally the on-ramp metering is concerned according to the queuing theory and the threshold value inequality is given for the better control to the on-ramp traffic.

Re-Evaluation of Ramp Design Speed Criteria: Review of Practice and Data Collection Plan, Michael Hunter and Randy Machemehl, Center for Transportation Research, University of Texas at Austin, Research Report 1732-1, April 1997.
http://www.utexas.edu/research/ctr/pdf_reports/1732_1.pdf
From the abstract: Several studies have raised questions about the appropriateness of the AASHTO minimum allowable ramp design speed. Questions have also been raised about the adequacy of high-speed ramp lengths designed by AASHTO criteria. A conceptual data collection plan has been designed to provide information that will answer questions regarding current criteria.

Capacity and Throughput

Managed Lane Strategies Feasible for Freeway Ramp Applications, Beverly Kuhn, Kevin Balke, Nadeem Chaudhary, Debbie Jasek, Ganesh Karkee, Kwaku Obeng-Boampong, Jeffrey Shelton and Steven Venglar, Texas Transportation Institute, January 2008.
http://tti.tamu.edu/documents/0-5284-2.pdf
Though this research is primarily an investigation of managed lanes (such as HOV or toll lanes) as an alternative to ramp metering, some of the methodologies and data may be of interest to Caltrans, such as the following tables:

- Tables 11 through 15, Average Mainline Running Speed (mph) with and without Ramp Metering Active for five different lengths of acceleration lanes.
- Tables 16 through 20, Difference in Average Running Speed (mph) on the Mainlane of the Freeway with and without Ramp Metering Active for five different lengths of acceleration lanes.
- Tables 21 through 25, Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering for five different lengths of acceleration lanes.
- Tables 26 through 30, Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering for five different lengths of acceleration lanes.
- Table 31, Summary of "Best Fit" Regression Equation for Estimate Non-Meter Ramp Demand to Obtain Equivalent Operations with Ramp Metering.

"Model Predictive Control for Ramp Metering of Motorway Traffic: A Case Study," T. Bellemans, B. De Schutter and B. De Moor, *Control Engineering Practice*, Vol. 14, No. 7, 2006: 757-767.
http://doclib.uhasselt.be/dspace/bitstream/1942/1490/1/Model%20predictive.pdf
The scope of this paper includes two methods to calculate dynamic or traffic responsive metering rates. The paper finds that "[t]he presented simulations are indicative for the reduction in the total time spent (on the studied motorway and on the on-ramps) that can be achieved by ramp metering during a typical morning rush hour."

Queue Management and Sensoring

"Analysis of Queue Estimation Methods Using Wireless Magnetic Sensors," Rene O. Sanchez, Roberto Horowitz and Pravin Varaiya, *Transportation Research Record*, Vol. 2229, 2011: 34-45.
http://trb.metapress.com/content/7l66qk832xu7u3t2/
From the abstract: Four queue estimation methodologies were studied with wireless magnetic sensors installed on a single-lane loop on-ramp. These queue estimation methods were evaluated with available raw and processed sensor data retrieved from the test site through mobile data communication and downloaded from a server.

"Queue Management Techniques for Metered Freeway On-Ramps," Anastasia D. Spiliopoulou, Diamantis Manolis, Ioannis Papamichail and Markos Papageorgiou, *Transportation Research Record*, Vol. 2178, 2010: 40-48.
http://trb.metapress.com/content/ah16803466424m7t/
From the abstract: A recently proposed ramp queue controller [was] investigated in conjunction with the local ramp-metering algorithm ALINEA. Microscopic simulation [was] used to compare the queue controller with a popular queue override scheme that is based on specifically designed scenarios and evaluation criteria. It [was] found that the queue controller outperforms the queue override and leads to fewer instances of ramp queue spillover.

"Experiment to Improve Estimation of Vehicle Queue Length at Metered On-Ramps," Jingcheng Wu, Xia Jin, Alan J. Horowitz and Daqing Gong, *Transportation Research Record*, Vol. 2099, 2009: 30-38.
http://trb.metapress.com/content/r7u775841026302g/
From the abstract: Two types of algorithms for on-ramp queue estimation are discussed: a Kalman filter and a conservation model. A volume-balancing ratio is introduced to both models to account for unavoidable detector miscounting behavior. Estimation results are compared with queue data observed in the field.

"Overview of Traffic Signal Operation Policies for Ramp Metering," Markos Papageorgiou and Ioannis Papamichail, *Transportation Research Record*, Vol. 2047, 2008: 28-36.
http://trid.trb.org/view.aspx?id=847664
From the abstract: A ramp metering control algorithm includes typically two distinct components: the (most important) control strategy, which makes real-time decisions on the ramp exit flow to be implemented, and the translation of this decision into specific traffic light settings according to the applied metering policy. This study focuses on the second component, providing an overview of practiced metering policies along with a discussion of their advantages and shortcomings.

Ramp Metering, University of Minnesota Center for Transportation Studies, 2012.
http://www.its.umn.edu/Research/FeaturedStudies/rampmeter.html
This web page lists studies that evaluate the control algorithms of ramp meters using simulation and modeling techniques—topics that are largely of secondary interest to Caltrans for this Preliminary Investigation.

Standard ramp metered entrance details

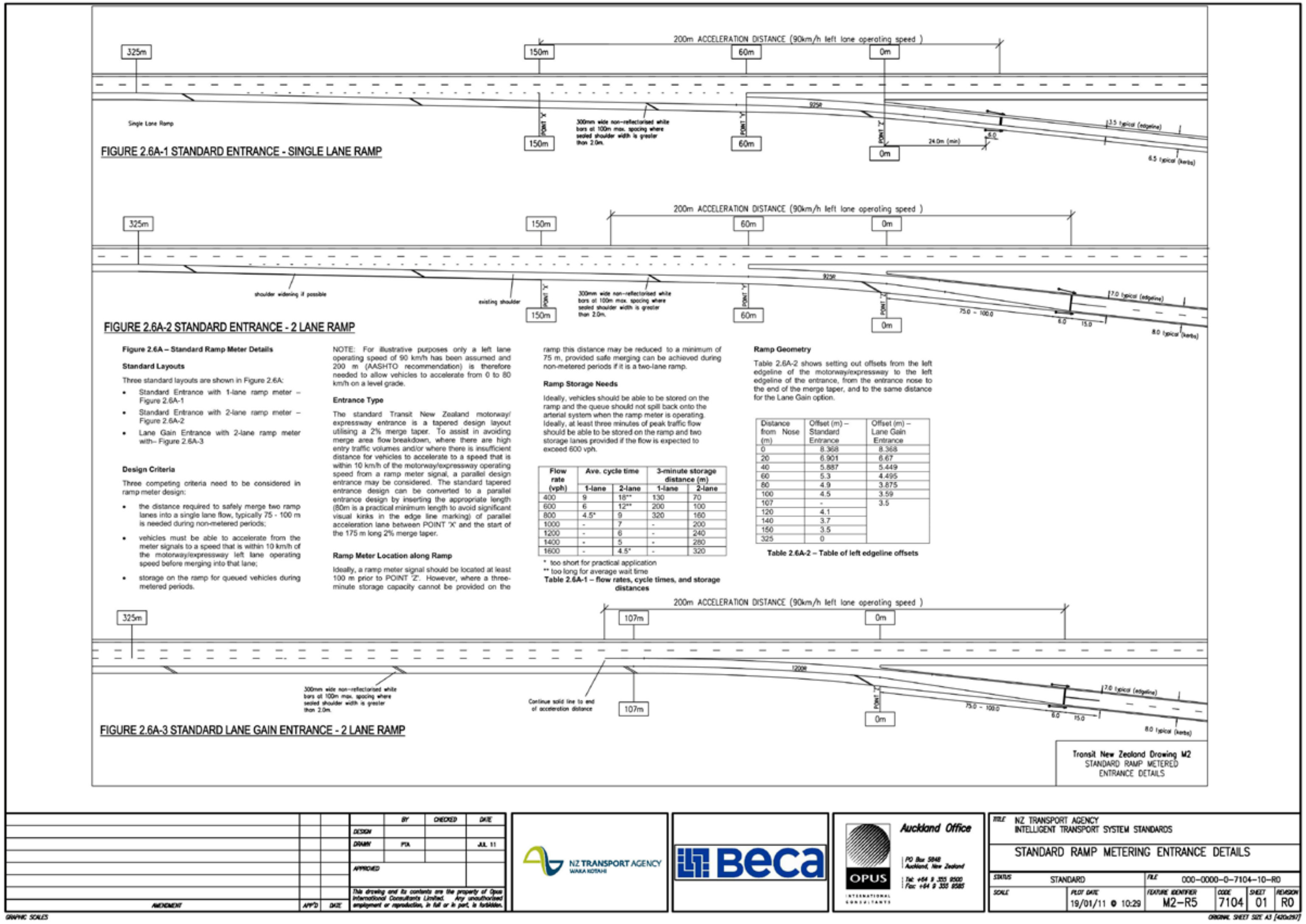

Figure 2.6A – Standard Ramp Meter Details

Standard Layouts

Three standard layouts are shown in Figure 2.6A:

- Standard Entrance with 1-lane ramp meter – Figure 2.6A-1
- Standard Entrance with 2-lane ramp meter – Figure 2.6A-2
- Lane Gain Entrance with 2-lane ramp meter with– Figure 2.6A-3

Design Criteria

Three competing criteria need to be considered in ramp meter design:

- the distance required to safely merge two ramp lanes into a single lane flow, typically 75 - 100 m is needed during non-metered periods;
- vehicles must be able to accelerate from the meter signals to a speed that is within 10 km/h of the motorway/expressway left lane operating speed before merging into that lane;
- storage on the ramp for queued vehicles during metered periods.

NOTE: For illustrative purposes only a left lane operating speed of 90 km/h has been assumed and 200 m (AASHTO recommendation) is therefore needed to allow vehicles to accelerate from 0 to 80 km/h on a level grade.

Entrance Type

The standard Transit New Zealand motorway/expressway entrance is a tapered design layout utilising a 2% merge taper. To assist in avoiding merge area flow breakdown, where there are high entry traffic volumes and/or where there is insufficient distance for vehicles to accelerate to a speed that is within 10 km/h of the motorway/expressway operating speed from a ramp meter signal, a parallel design entrance may be considered. The standard tapered entrance design can be converted to a parallel entrance design by inserting the appropriate length (80m is a practical minimum length to avoid significant visual kinks in the edge line marking) of parallel acceleration lane between POINT 'X' and the start of the 175 m long 2% merge taper.

Ramp Meter Location along Ramp

Ideally, a ramp meter signal should be located at least 100 m prior to POINT 'Z'. However, where a three-minute storage capacity cannot be provided on the ramp this distance may be reduced to a minimum of 75 m, provided safe merging can be achieved during non-metered periods if it is a two-lane ramp.

Ramp Storage Needs

Ideally, vehicles should be able to be stored on the ramp and the queue should not spill back onto the arterial system when the ramp meter is operating. Ideally, at least three minutes of peak traffic flow should be able to be stored on the ramp and two storage lanes provided if the flow is expected to exceed 600 vph.

Flow rate (vph)	Ave. cycle time		3-minute storage distance (m)	
	1-lane	2-lane	1-lane	2-lane
400	9	18**	130	70
600	6	12**	200	100
800	4.5*	9	320	160
1000	-	7	-	200
1200	-	6	-	240
1400	-	5	-	280
1600	-	4.5*	-	320

* too short for practical application
** too long for average wait time

Table 2.6A-1 – flow rates, cycle times, and storage distances

Ramp Geometry

Table 2.6A-2 shows setting out offsets from the left edgeline of the motorway/expressway to the left edgeline of the entrance, from the entrance nose to the end of the merge taper, and to the same distance for the Lane Gain option.

Distance from Nose (m)	Offset (m) – Standard Entrance	Offset (m) – Lane Gain Entrance
0	8.368	8.368
20	6.901	6.67
40	5.887	5.449
60	5.3	4.495
80	4.9	3.875
100	4.5	3.59
107	-	3.5
120	4.1	
140	3.7	
150	3.5	
325	0	

Table 2.6A-2 – Table of left edgeline offsets