DEPARTMENT OF TRANSPORTATION

Model Systems Engineering Document

ITS Application: Ramp Metering

May 24, 2019
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Contents

Acronyms

ARC-IT	National Architecture Reference for Cooperative and Intelligent Transportation
ATMS	Advanced Traffic Management Software
CAV	Connected and Automated Vehicle
IRIS	Intelligent Roadway Information System
ITS	Intelligent Transportation System
LAN	Local Area Network
MnDOT	Minnesota Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NRTL	Nationally Recognized Testing Laboratory
OBE	On-Board Equipment
OSHA	Occupational Safety and Health Administration
RSM	Roadside Safety Message
RSU	Roadside Unit
RTMC	Regional Transportation Management Center
SEA	Systems Engineering Analysis
TTC	Temporary Traffic Control
VPN	Virtual Private Network
WAN	Wide Area Network

Purpose and Description of Application

Document Purpose

This document is intended to support the Systems Engineering Analysis (SEA) activities for the Minnesota Department of Transportation (MnDOT) and other local transportation agencies within Minnesota as they consider, plan, develop, design, implement, and operate ramp metering. The content of this document will be a systems engineering analysis resource to support project compliance as set forth in 23 CFR Section 940 (Rule 940). This document can be used in conjunction with the Minnesota Statewide Regional Intelligent Transportation System (ITS) Architecture and related systems engineering resources to complete an ITS Systems Engineering project-specific checklist as part of the initial analysis of applications considered for implementation. To access the available checklists for ITS-related deployments, visit the MnDOT Systems Engineering web page at: https://www.dot.state.mn.us/its/systemsengineering.html.

In situations where projects are not consistent with this systems engineering document, the contents of this document may be used as a base to support the development of project specific systems engineering documents, including a concept of operations, functional requirements, and test plans specific to the project.

Description of Application – Ramp Metering

Ramp meters are traffic signals on highway entrance ramps. Ramp meters either flash yellow lights or proceed from red to green to yellow, allowing vehicles to enter the freeway one at a time. As operations of CAVs expand, several data exchanges between ramp meters and Connected and Automated Vehicles (CAVs) are anticipated, and these are presented in this document. Ramp meter rates (i.e. the time between green lights allowing subsequent vehicles to enter the freeway) are either determined by time of day algorithms or manually determined by operators in the Regional Transportation Management Center (RTMC).

Ramp Metering Environment/Components

Table 1 presents the environment/components included in ramp metering and describes the function of each.

Table 1: Ramp Metering Environment/Components

Environment/Component	Function
1. Ramp Control Signal	Ramp meter devices that are located along freeway on-ramps and serve as the visual display of current status to travelers (e.g. green, yellow, red). Ramp control signals are most often permanently installed, but temporary deployments may be used when needed (e.g. during roadway construction).
2. Ramp Meter Signal Controllers	Equipment with software that controls the operation of ramp control signals. Ramp meter signal controllers commonly accept commands from the Advanced Traffic Management Software (ATMS) to operate the ramp control signals. Ramp meter signal controllers may ingest and process data from other sources, such as mainline traffic detection and/or ramp traffic detection and exchange data with other nearby

Environment/Component	Function
	ramp meter signal controllers, local traffic signal controllers and/or a central traffic signal control system to run algorithms and carry out local-responsive ramp metering control.
3. Ramp Meter	The ramp control signal and the ramp meter signal controller operating together as a collective ramp meter unit.
4. Mainline Traffic Detection	Detection sources and traffic data -- including volumes, lane occupancy, and/or speeds – collected along the mainline of freeways in the vicinity of ramp control signals and communicated to ramp meter signal controllers for local-responsive ramp metering control, or to ATMS for data processing by ramp meter algorithms.
5. Ramp Traffic Detection	Detection equipment and traffic data collected along on-ramps leading up to permanent ramp meters, to detect the presence of vehicles and queues approaching ramp control signals.
6. Advanced Traffic Management Software (ATMS)	The software used by traffic operations personnel to monitor traffic conditions and control infrastructure systems. Examples of the ATMS relationship to ramp meters are that the ATMS may house the ramp meter algorithm, compare traffic detection data against the algorithm, and communicate metering rates to each meter.
7. Local Traffic Signal Controllers	Equipment that is responsible for controlling the traffic signals. Local traffic signal controllers at intersections in the vicinity of ramp meters may exchange data with ramp meter signal controllers and adjust signal timing at traffic signals near ramp meters, to help reduce traffic queues at ramp meters.
8. Central Traffic Signal Control System	A central software system that may exchange data with ramp meter signal controllers and adjust signal timing at traffic signals near ramp meters, to help reduce traffic queues at ramp meters.
9. Supporting Communications	The communications infrastructure to allow data communications between the ramp meter and other systems such as the ATMS. (See details in the *Model System Engineering Document, ITS Application: Communications* document.)
10. CAV Infrastructure Systems	The systems deployed by the DOTs to communicate with on-board units within CAVs. The ramp control signals may send and receive data with the CAV infrastructure system, or the ATMS may send data describing current ramp meter operations directly to the CAV infrastructure systems.
11. CAVs	The vehicles and on-board applications that communicate with CAV infrastructure systems and other CAVs. There may be situations that exist where ramp meters communicate directly with the CAVs.

The primary ramp metering components and related systems are illustrated in Figure 1.

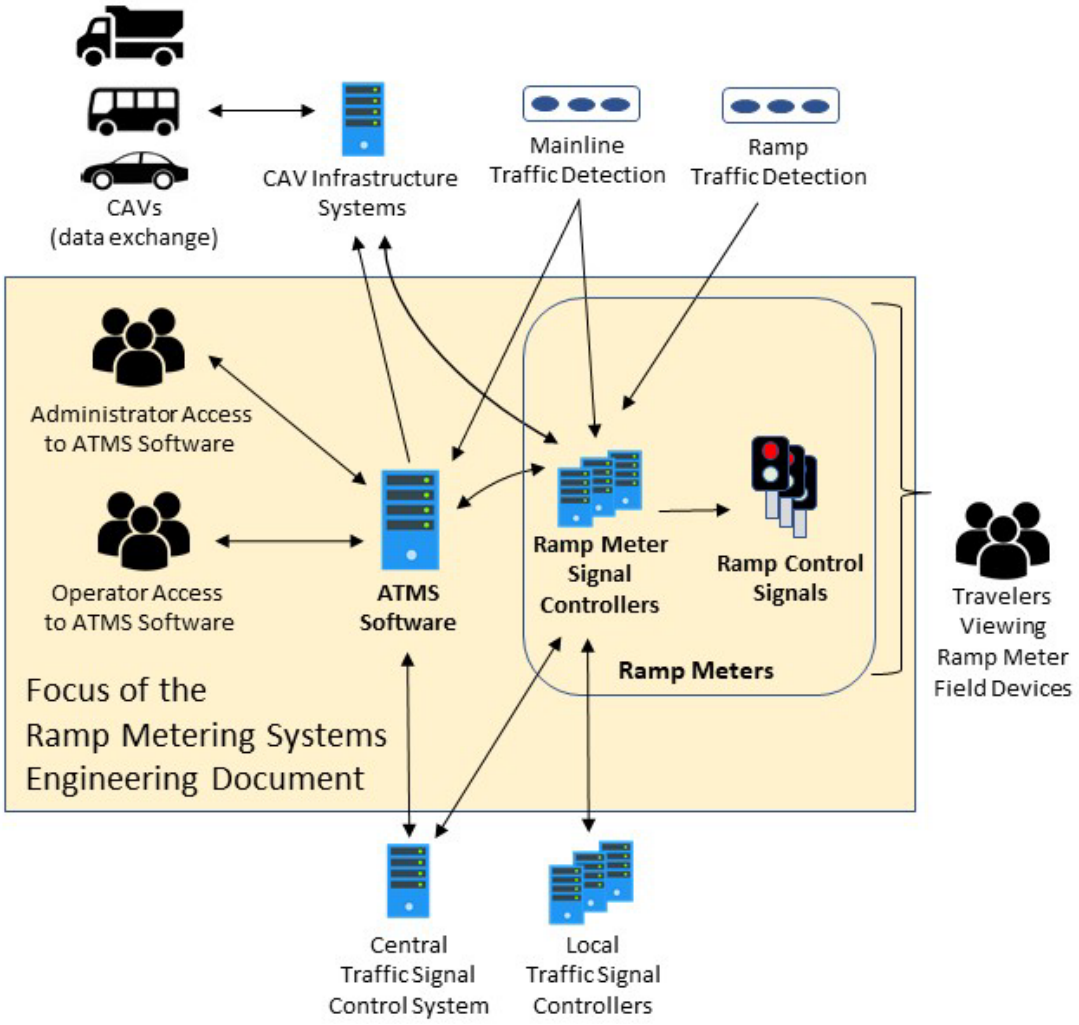

Figure 1: Illustration of Primary Ramp Metering Application Components and Related Systems/Users

Examples of Communications Technologies Supporting Ramp Metering

The ramp metering application relies upon a number of communications technologies (detailed in a separate document - *Model System Engineering Document, ITS Application: Communications*) to provide ramp metering capabilities via field devices to eventual end users. The following table summarizes examples of communications technologies used today.

Table 2: Examples of Current Communications Supporting Ramp Metering Applications

Ramp Metering Application Communications	Communications Technologies Supporting Ramp Metering Applications
ATMS to ramp meter signal controllers	• **Long range communications** – Ethernet connections using fiber or copper mediums to communicate ramp meter information from the ATMS to ramp meter signal controllers. • **Short-range wireline or wireless communications** – Ethernet or serial connections using fiber or copper mediums or wireless connections using WiFi, microwave, or FM radio, depending on local conditions, to support two-way communications over the short distances from the ramp meter signal controller to ramp control signal. • **DOT operated Local Area Network (LAN) or Wide Area Network (WAN)** – Private communications network that allows a connection between ramp meter signal controllers and the ATMS with standard security concerns. • **Virtual Private Network (VPN) over public internet** – Secure and encrypted communications over less secure networks and the public internet allow communication of ramp meter information from the ATMS to ramp meter signal controllers in locations where agency owned communications are not practical.
Ramp meter signal controller to CAV infrastructure system	• **Short-range wireline or wireless communications** – Ethernet or serial connections using fiber or copper mediums or wireless connections using WiFi, microwave, or FM radio, depending on local conditions, to support two-way communications over the short distances from the ramp meter signal controller to the CAV infrastructure system. • **DOT operated LAN or WAN** – Private communications network that allows a connection between the ramp meter signal controller and CAV infrastructure system with standard security concerns. • **Commercial wireless communications** – Services provided by third party providers over commercial networks, such as cellular and WiFi, allow wireless communications of ramp meter information from the ramp meter signal controller to CAV infrastructure systems. • **VPN over public internet** – Secure and encrypted communications over less secure networks and the public internet allow communication of ramp meter information from the signal controller to CAV infrastructure system in locations where agency owned communications are not practical.
Ramp meter signal controller to CAVs	• **Short-range, wireless, low latency communications** – Extremely low latency communications from the ramp meter signal controller to CAVs that are able to support credentials-based security protocols within a line of sight range of generally 300 meters or less.

Stakeholders and Typical Conditions

Stakeholders

Table 3 identifies the stakeholder groups that interface with one or more aspects of ramp metering deployment and operations.

Table 3: Stakeholder Groups Interfacing with Ramp Metering Deployment and Operation

Stakeholder	Description
Travelers	Vehicle drivers and passengers operating traditional vehicles and CAVs who are entering freeway segments with ramp meter devices located at the on-ramp.
Operators/Operations	RTMC operators or other agency operators responsible for occasionally manually activating or de-activating ramp meters, viewing nearby cameras to verify ramp meters are operating properly, and in some situations temporarily overriding the ramp meter algorithm. This also includes the term "operations" which refers to the overall operation of the transportation network, which is often enhanced by automated ramp metering functions that require minimal or no interaction by operators.
Administrators	A combination of operators and technical staff responsible for configuring (e.g. time of day automatic activation parameters or pre-determined metering rates), updating, and verifying the status of ramp meters.
Technicians and Installers	Technical staff responsible for installing, maintaining, and troubleshooting the ramp control signals and the ATMS software system(s) that control the ramp meters (e.g. Intelligent Roadway Information System (IRIS)). May include DOT staff, contractors, and consultants, performing actions both in the field and remotely.
CAV Infrastructure Systems and CAVs	External systems that include both CAV infrastructure systems (systems operated by MnDOT) and CAV systems (on-board units in the vehicles) that support CAV operations.

Typical and Local Conditions

Ramp meters are commonly installed on the side of the on-ramps on the approach to the freeways in metropolitan areas. Site selection is typically a combination of the following key factors:

1. Identifying locations prone to congestion that would benefit from creating gaps in the traffic merging on to the freeway;
2. Identifying or creating the infrastructure that can 'store' a queue of vehicles behind the meter while they wait to enter the freeway;
3. Identifying unique locations where on-ramps include merging ramps, and travelers benefit from slowing or managing flow during peak periods; and
4. For temporary ramp meters: Identifying locations that are impacted by road construction activities that displace or relocate on-ramps.

Stakeholder Needs

Table 4 identifies a series of problems or challenges and the related needs for each stakeholder identified above.

Table 4: Stakeholder Needs

Problem/Challenge	Needs (As a Result of the Problem/Challenge)
Travelers Needs	
- Travelers on the freeways encounter large volumes of vehicle merging at the on-ramps, causing safety and mobility issues with merging traffic.	***Need 1: Reduce Conflicts with Merging Traffic*** Travelers need smooth merging of vehicles entering freeways at on-ramps.
- Without ramp metering, congestion is more common and causes stopped traffic and queues to form.	***Need 2: Reduce Freeway Congestion*** Travelers need congestion that causes stopped traffic to be reduced in order to maintain movement of the freeway and improve safety.
- Travelers unfamiliar with ramp metering may be confused by their operation.	***Need 3: Ramp Meter Understanding*** Travelers need ramp meters and supporting signs to clearly articulate expectations of drivers approaching and passing through the ramp meter.
- Travelers may be frustrated by travel times that are not consistent from day to day along their typical routes.	***Need 4: Mobility and Travel Time Reliability*** Travelers on the freeway need ramp meters to optimize mobility and increase the reliability of their travel times, for their trip routes that are consistent on a daily basis, such as commutes during AM and PM peak periods.
Operators/Operations Needs	
- Traffic management devices in the field must be controlled by operators either on-site or without requiring operators to be local to the device.	***Need 5: Ramp Meter Control*** Operators need to be able to turn the ramp meters on or off and also have the ability to override ramp meter settings remotely, in addition to on-site.
- Without reliable verification, the operators cannot be certain if the ramp meters are functioning properly.	***Need 6: Ramp Meter Monitoring*** Operators need to be able to monitor the operational status of each ramp meter from ATMS from locations remote to the ramp meters.
- Ramp meters require meter rates in response to current conditions.	***Need 7: Automated Ramp Meter Control*** Operators/operations need ramp meters to activate and determine meter rates automatically.
- If queues from ramp metering back up too far, they can present a hazard to upstream freeways or arterials approaching the metered on-ramp.	***Need 8: Extensive Ramp Back-ups and Automated Adjustments*** Operators/operations need mechanisms to prevent the vehicles queued at ramp meters from extending into upstream lanes of traffic, either from approaching freeways, beyond the queue storage area, or from arterials where vehicles enter the on-ramp.

Problem/Challenge	Needs (As a Result of the Problem/Challenge)
Administrators Needs	
- Ramp meter operation requires configuration of ramp control signals and periodic updates to the device.	***Need 9: Ramp Meter Configuration*** Administrators need to be able to configure ramp control signals, either remotely or at the ramp meter.
Technicians and Installers Needs	
- Proper use of ramp meters requires communications, power, and installation on structures at the deployment site.	***Need 10: Ramp Meter Supporting Infrastructure*** Technicians and installers need power, communications, and support structures to be available at the site where ramp meters are deployed.
- Ramp meters deployed in the field must not harm technicians, installers, or anyone in vicinity of the ramp meters.	***Need 11: Safety Standards*** Technicians and installers need the ramp meters to adhere to appropriate safety standards, specifications, and protocols.
- Communications that enable data exchange with central systems are critical for ramp metering operations.	***Need 12: Communication to ATMS*** Technicians and installers need the ATMS to communicate with ramp meter signal controllers and with a central traffic signal controller as available.
- Some situations may benefit from communications that allow local-responsive ramp metering strategies and automatic adjustments to nearby traffic signals.	***Need 13: Communication Among Signal Controllers*** Technicians and installers need ramp meter signal controllers to communicate to one another, to local traffic signal controllers, and to a central traffic signal controller.
CAV Infrastructure Systems and CAVs Needs	
- MnDOT may deploy CAV infrastructure systems that communicate ramp meter status to CAVs, either through roadside units (RSUs) or cloud-based communications.	***Need 14: CAV Message Receipt*** CAV infrastructure systems may need a mechanism to receive ramp meter status (e.g. activated or not activated, current metering rates).
- In some situations, CAVs may benefit from direct data exchanges with Ramp Control Signals.	***Need 15: CAV Local Connection*** CAVs may need a mechanism to communicate directly with ramp meters.

Operational Concepts

The previous section defined a series of stakeholders that are expected to interact with ramp meters and their needs likely to be addressed by ramp meters. This categorization will be further used in this section to describe the operational concept for ramp meters from each user's perspective. The operational concept is intended to help each user see how their needs have been interpreted and how the ramp meters are expected to address their needs. It is presented in a sequential manner from each user's perspective, with the needs included in the tables for reference.

Travelers' Perspective

Table 5 describes the ramp metering operational concepts from the travelers' perspective, and relates each concept to a need, as defined in the previous section.

Table 5: Ramp Metering Operational Concepts - Travelers' Perspective

Need (Travelers' Perspective)	Operational Concept
Travelers' Perspective linked to ***Need 1: Reduce Conflicts with Merging Traffic***	1.1 Travelers approaching a ramp meter will stop and queue at the ramp meter when the meter's indication is red. 1.2 As the ramp meter turns from red to green, travelers will proceed to enter the freeway in a single-file fashion and experience minimized conflicts merging into freeway traffic. 1.3 Travelers at metered on-ramps will merge into freeway traffic at timed intervals and will therefore not be surrounded by several other vehicles trying to approach the freeway merge at the same time.
Travelers' perspectives linked to ***Need 2: Reduce Freeway Congestion***	2.1 Travelers on freeways with metered ramp control will experience less stop and go traffic where merging from ramps occurs, decreasing the potential congestion-related crashes.
Travelers' perspectives linked to ***Need 3: Ramp Meter Understanding***	3.1 Travelers approaching a ramp meter from a high-speed freeway exit or in areas where site distance to the ramp meter is limited will see a sign indicating that ramp meters are ahead or that ramp meters are activated when the sign's beacons are flashing. 3.2 Travelers may approach a queue of vehicles at the ramp meter and see a sign indicating to form 2 lanes when metered. 3.3 Travelers will see ramp meters on both sides of the on-ramp, along with signs indicating one car on green. 3.4 Travelers will stop at the ramp meter's red indication and proceed when the ramp meter indication is green.

Need (Travelers' Perspective)	Operational Concept
Travelers' perspectives linked to ***Need 4: Mobility and Travel Time Reliability***	4.1 Travelers driving on their typical routes will experience relatively consistent travel times on a daily basis, especially during morning and evening commute periods. 4.2 Ramp meters will have metering rates that are assessed regularly and adjusted as needed to account for freeway travel patterns that change over time, to optimize mobility and maximize travel time reliability.

Operators/Operations' Perspective

Table 6 describes the ramp metering operational concepts from the operators/operations' perspective, and relates each concept to a need, as defined in the previous section.

Table 6: Ramp Metering Operational Concepts – Operators/Operations' Perspective

Need (Operators/Operations' Perspective)	Operational Concept
Operators/Operations' perspectives related to ***Need 5: Ramp Meter Control***	5.1 Operators will use the ATMS to activate or de-activate ramp meters during rare situations when manual intervention is needed. 5.2 Operators will use the ATMS to override ramp meter algorithms to adjust metering rates, as needed depending on the status of queues at ramp meters or nearby freeway congestion levels.
Operators/Operations' perspectives related to: ***Need 6: Ramp Meter Monitoring***	6.1 Operators will use the ATMS to periodically monitor ramp meter operations during periods of freeway congestion. 6.2 Operators may use nearby cameras to verify ramp meters are operating properly. 6.3 Operators may rely on field staff to perform on-site verification of ramp meter status and operations. 6.4 Operators will use the ATMS to view the status of ramp meters, including the operational status, whether or not communications to the ramp meter are functioning, and the self-diagnostics performed by the ATMS control algorithms. 6.5 Operators will use the ATMS to view each ramp meter's current activation status. 6.6 Operators will use the ATMS to view the current ramp metering rates. 6.7 Operators will use the ATMS to view the ramp meter's pre-defined conditions, including time of day activation and de-activation times, and metering rates.

Need (Operators/Operations' Perspective)	Operational Concept
Operators/Operations' perspectives related to: ***Need 7: Automated Ramp Meter Control***	7.1 Operators will have minimal to no interaction with ramp meters that have automated ramp meter control. 7.2 Operators will rely on the ATMS to receive traffic detection data from the adjacent freeway and from the on-ramp's ramp traffic detection to run pre-defined algorithms that determine appropriate metering rates. 7.3 Operators will rely on the ATMS to communicate commands to ramp meters, either at pre-defined metering rates or at metering rates that adjust automatically according to congestion levels on the freeway. 7.4 Operators will rely on the ATMS to automatically activate and de-activate flashing beacons on ramp meter approach signs in locations where those signs are in place. 7.5 In situations where the ATMS is using automated algorithms to determine ramp metering rates, operators are not expected to manually monitor the changing conditions and adjust metering rates, but they may perform some actions such as periodically viewing traffic conditions at ramp locations. 7.6 External systems may perform the analysis to determine pre-defined ramp metering rates. In these situations, the ATMS would accept and act upon these commands from external systems.
Operators/Operations' perspectives related to: ***Need 8: Extensive Ramp Back-ups and Automated Adjustments***	8.1 Ramp traffic detection at on-ramps in advance of ramp meters will detect when vehicle queues have exceeded a pre-determined maximum queue location. 8.2 Ramp traffic detection will communicate presence data to ramp meter signal controller(s) as excessive queues are detected. 8.3 Ramp meter signal controllers will ingest presence data and communicate it to the ATMS. 8.4 Ramp metering algorithms will automatically adjust ramp metering rates, as needed, to dissipate/flush extensive ramp queues. 8.5 Operators will not need to take action to dissipate/flush extensive ramp queues but will have the ability to override ramp meter settings as needed. 8.6 As excessive vehicle queues are detected by ramp traffic detection, ramp meter signal controllers may communicate to nearby local traffic signal controllers or to

Need (Operators/Operations' Perspective)	Operational Concept
	a central traffic control system, to trigger adjustments in traffic signal timing to reduce the inflow of traffic onto on-ramps. 8.7 The ATMS may communicate presence data to nearby local traffic signal controllers or a central traffic control system, to trigger adjustments in traffic signal timing at nearby traffic signals, to reduce the inflow of traffic onto on-ramps.

Administrators' Perspective

Table 7 describes the ramp metering operational concepts from the administrators' perspective, and relates each concept to a need, as defined in the previous section.

Table7: Ramp Metering Operational Concepts - Administrators' Perspective

Need (Administrators' Perspective)	Operational Concept
Administrators' perspectives related to: ***Need 9: Ramp Meter Configuration***	9.1 Administrators will configure the ramp control signals once they are installed. Configuration will link the ramp control signals to the ATMS software and will also include setting ramp meter parameters such as time of day, metering rates, and queue detection parameters. 9.2 Configuration will be conducted at site or remotely by using the ATMS. 9.3 In situations where the software/signal controller within the ramp control signal is upgraded, configuration may be required to maintain compatibility. 9.4 Administrators may perform portions of the configuration at the ramp control signal (in the field) or may configure the device remotely. 9.5 In situations where remote control of the ramp control signal is not possible, administrators at the site of the device will be able to connect a laptop to the device and control the activation, de-activation, and metering rates using the ramp control signal manufacturer software for control.

Technicians and Installers' Perspective

Table 8 describes the ramp metering operational concepts from the perspective of the technicians and installers of ramp meters, and relates each concept to a need, as defined in the previous section.

Table 8: Ramp Metering Operational Concepts – Technicians and Installers' Perspective

Need (Technicians and Installers' Perspective)	Operational Concept
Technicians and Installers' perspectives related to ***Need 10: Ramp Meter Supporting Infrastructure***	10.1 Site selection and preparation for ramp control signals will result in selection of devices with adequate supporting structures, such as a pole/post and footing. 10.2 Installation of the ramp control signals will include the necessary design and installation of supporting infrastructure, including power, communications, ramp meter signal visibility, ramp meter accessibility, etc.
Technicians and Installers' perspectives related to ***Need 11: Safety Standards***	11.1 Installers will only install ramp meters that are tested, certified, and labeled by a Nationally Recognized Testing Laboratory (NRTL) as acceptable under Occupational Safety and Health Administration (OSHA) regulations. 11.2 Technicians and installers will rely upon installation instructions and guidelines from the ramp meter vendor. 11.3 Technicians and installers will be responsible for performing appropriate temporary traffic control (TTC) in compliance with the Manual on Uniform Traffic Control Devices (MUTCD) when installing or performing field work on permanent or temporary ramp meters.
Technicians and Installers' perspectives related to ***Need 12: Communication to ATMS***	12.1 In situations where the ATMS runs ramp metering algorithms, technicians and installers will establish and maintain communications between the ATMS and ramp meter signal controllers. 12.2 In situations where the ATMS is communicating with a central traffic signal controller to communicate data related to ramp metering operations, technicians and installers will establish and maintain communication between the ATMS and the central traffic signal controller.
Technicians and Installers' perspectives related to ***Need 13: Communication Among Signal Controllers***	13.1 In situations where local-responsive ramp metering is deployed, technicians and installers will establish and maintain communications between multiple ramp meter signal controllers. 13.2 For ramp metering deployments that incorporate strategies that interact with nearby traffic signals operated by local traffic signal controllers, technicians and installers will establish and maintain communications between ramp meter signal controllers and local traffic signal controllers. 13.3 For ramp metering deployments that incorporate strategies that interact with nearby traffic signals operated by a central traffic signal controller, technicians and installers will establish and maintain communications between ramp

Need (Technicians and Installers' Perspective)	Operational Concept
	meter signal controllers and a central traffic signal controller.

CAV Infrastructure Systems and CAVs' Perspective

Table 9 describes the ramp metering operational concepts from the perspective of CAV infrastructure systems and vehicles, and relates each concept to a need, as defined in the previous section.

Table 9: Ramp Metering Operational Concepts - CAV Infrastructure Systems and CAVs' Perspective

Need (CAV Infrastructure Systems and CAVs' Perspective)	Operational Concept
CAV Infrastructure Systems perspectives related to ***Need 14: CAV Message Receipt***	14.1 CAV infrastructure systems responsible for creating Roadside Safety Messages (RSM) will benefit from information about the current status of ramp meters, such as activated or de-activated and current metering rates. 14.2 CAV infrastructure systems such as roadside units may benefit from sharing utilities (e.g. power, communications), and structures with ramp meters.
CAV infrastructure Systems and CAVs' perspectives related to ***Need 15: CAV Local Connection***	15.1 CAVs may receive messages from ramp meters and provide in-vehicle display of the current status of the ramp meter (e.g. red or green indication), or an alert to the driver based on the current status of the ramp meter. 15.2 CAVs may receive messages from ramp meters and provide in-vehicle display or an alert to the driver when the vehicle is approaching the ramp meter, such as "one car on green signal at ramp meter ahead." 15.3 Self-driving CAVs may receive messages from ramp meters and use the messages to determine when the vehicle is allowed to advance. 15.4 Self-driving CAVs may use on-board cameras to detect when ramp meters are green or red. 15.5 Ramp meters may receive messages from CAVs or CAV infrastructure systems indicating strings or platoons of vehicles that may require temporary adjustments to metering rates (either to allow a string/platoon to continue together on an on-ramp or to hold vehicles on a ramp as a platoon or string passes). 15.6 Ramp meters may receive messages from CAVs or automated vehicles indicating the planned time of arrival at ramp meters, allowing ramp meters to adjust rates based on anticipated traffic volumes.

Operational Scenarios/Roles and Responsibilities

Roles and Responsibilities

The *Operational Concept* section defined interactions of the primary stakeholders with ramp metering and supporting software. The table below provides a high-level summary of the roles and responsibilities of the stakeholder groups.

Table 10: Operation and Maintenance Roles and Responsibilities

User Group	Role/Responsibility
Travelers	• Stop and queue at the appropriate location when ramp meter indications are red. Proceed to the freeway when the ramp meter indication is green or proceed with caution when flashing yellow.
Operators	• Activate or de-activate ramp meters and override ramp meter algorithms, as needed. • Monitor ramp meter operations, operational status, and metering rates. •
Administrators	• Configure ramp control signals and link to the ATMS software. • In situations where remote control of the ramp control signal by operators is not possible, administrators at the site of the device will be able to connect to the device.
Technicians and Installers	• Install ramp control signals and ramp meter signal controllers and perform appropriate traffic control, with consideration to the MUTCD. • Establish and maintain communications between the ATMS and ramp meter signal controllers. • If appropriate, establish communications between the ramp meter signal controllers and the central traffic signal controller and local traffic signal controllers.

Operational Scenarios

Scenarios are intended to describe how users will interact with the ramp metering applications and specifically to provide a temporal description of the sequence of events. The following scenarios briefly describe how users will be impacted and how they are expected to respond.

- Scenario A: Typical Weekday
- Scenario B: Ramp Incident
- Scenario C: Traffic Backup on On-Ramp
- Scenario D: CAVs Interaction with Ramp Meters

Scenario A: Typical Weekday

On a typical weekday morning within the Twin Cities, along the limited access freeways, detailed volume and lane occupancy data for each lane of traffic is collected by traffic detection field devices. These volumes and lane occupancies are periodically communicated to IRIS – MnDOT's ATMS, a centrally located traffic data management system. Using the volume and lane occupancy data ingested from traffic detection devices, the ATMS continually calculates traffic speeds and densities along the freeway.

As the morning commute period begins, ramp meters activate based on traffic responsive algorithms. Once activated, the ramp metering algorithm within the ATMS uses computed traffic density data to determine ramp meter rates. As traffic densities increase on 169 southbound near 49th Avenue, the ramp meter red indication is extended based on the automated ramp meter algorithm. Travelers view the ramp meter and briefly stop their vehicles during the ramp meter's red indication, until a green indicator allows their vehicle to advance into the freeway stream. At approximately 8:45 AM, as volume and lane occupancy data from traffic detection along 169 southbound near 49th Avenue return to free-flow conditions, the ramp meter algorithm reduces the red indication period. Eventually, as the morning peak concludes, the ramp meters throughout the metro area return to flashing yellow.

Scenario B: Ramp Incident

During an AM peak period, ramp meters are operating as they typically do. At approximately 7:30 AM, TMC operators are alerted of a crash on a ramp that is blocking the flow of traffic on the ramp. An operator in the RTMC uses traffic cameras to view the crash location and notices that responders have arrived to direct vehicles around the crash. The RTMC operator makes the decision to temporarily turn off the ramp meter to allow the traffic to follow the advice of the on-scene responders directing traffic around the crash. At 8:15 AM the incident is cleared, and the RTMC operator restarts the ramp meter to the pre-set conditions.

Scenario C: Traffic Backup on On-Ramp

During the PM peak, ramp meters are operating according to the typical time-of-day plan, following the green, yellow, red sequence. At one on-ramp, the combination of heavier than normal traffic entering the on-ramp combined with longer than typical red-light times has resulted in a queue forming further up the on-ramp than normal. As the queue extends beyond the ramp traffic detectors, pre-configured algorithms automatically adjust the ramp meter rate to decrease the time between green lights and allow the queue on the ramp to dissipate before it extends into the upstream surface street. As the traffic entering the ramp dissipates, the ramp meter rate returns to the normal rate, eventually the PM peak period ends, and the ramp meter returns to flashing yellow.

Scenario D: CAVs Interaction with Ramp Meters

At a time when a high number of CAVs are operational in Minnesota, vehicles on the on-ramp may receive communications from the ramp meter indicating the status (e.g. red, yellow, green) of the meter. Depending upon the level of autonomy the vehicle is operating in, the vehicle may either proceed autonomously or provide the driver a prompt that it is safe to proceed down the remainder of the on-ramp. At the same time, as strings of CAVs (i.e. multiple vehicles traveling together under autonomous control of acceleration/deceleration to maintain desired time gaps between vehicles) travel down the freeway, they may receive wireless data from the ramp meter alerting them to the time sequence of when green lights allow merging vehicles to proceed down the ramp. These strings of vehicles may use this data to create space gaps to allow merging vehicles to safely enter the freeway.

System Requirements

System requirements are verifiable details that define what a system will do, but not how the system will do it. Requirements can describe the functional, performance, interface, communications, operational, and maintenance conditions of what a system will do.

Requirements for ramp metering (ramp control signals, controllers, and supporting systems) are listed in the table below first by needs (column 1). These represent the needs of all the stakeholders described in the *Stakeholder Needs and Typical Conditions* section. Based on each need and on the operational concepts presented in the *Operational Concepts* section, one or more system requirements (column 2) are described. Requirements are all numbered to facilitate traceability back to the original needs and further traceability through design and validation.

Table 11: Ramp Metering Requirements by Need

Need	System Requirement
Travelers	
1. Travelers need smooth merging of vehicles entering freeways at on-ramps.	1.1. In locations that experience recurring unreliable travel times, permanent ramp meters shall be considered to manage the rate of flow of traffic entering freeways. 1.2. In situations where displacement of ramp meters occurs, such as during work zones lasting approximately the entire construction season, temporary ramp meters shall be considered to manage the rate of flow of traffic entering freeways. 1.3. In locations where temporary ramp configurations (e.g. during construction or maintenance activities) create situations where merging into the mainline is difficult, temporary ramp metering shall be considered to manage the speed and rate of traffic entering the freeways. 1.4. Ramp meters shall be located strategically along freeway corridors to enhance freeway traffic management and travelers' merging experience. 1.5. Ramp meter deployments should consider MUTCD requirements during design and placement.

Need	System Requirement
2. Travelers need congestion that causes stopped traffic to be reduced in order to maintain movement of the freeway and improve safety.	2.1. Ramp meters shall be located at on-ramps at intervals spaced along freeway corridors to minimize freeway congestion and merging conflicts, based on historical, current, and projected traffic demand along the corridor. 2.2. Ramp metering rates shall be determined based on proven ramp metering design parameters and traffic patterns along the corridor, to minimize congestion along the corridor and to minimize merging conflicts.
3. Travelers need ramp meters and supporting signs to clearly articulate expectations of drivers approaching and passing through the ramp meter.	3.1. Ramp control signals shall be located for visibility from the full width of the on-ramp. 3.2. Ramp control signals shall be located so the signals are visible from a distance that is appropriate for the on-ramp on which it is installed, considering the local speed limit and sight distance. 3.3 At each ramp meter location, one ramp control signal shall be placed on both sides of the on-ramp, adjacent to one another. 3.4 When ramp meters are placed at on-ramps where approaching traffic is entering from a high-speed freeway or where sight distance is limited, signage shall be placed in advance of the ramp meter, indicating that a ramp meter is ahead or that a ramp meter is activated when the sign's beacons are flashing. 3.5 Signage shall be placed in advance of the ramp meter indicating form two lanes when metered. 3.6 Signage shall be placed at the ramp control signal to indicate stop here on red. 3.7 Signage shall be placed at the ramp control signal to indicate one car on green. 3.8 All signage for ramp meter deployments shall be designed and placed in compliance with the MUTCD. 3.9 Ramp control signals and all associated field components shall have the ability to

Need	System Requirement
	perform in extreme cold conditions experienced in Minnesota. 3.10 Ramp control signals and all associated field components shall function properly in extreme heat conditions. 3.11 Ramp control signals and all associated field components shall be constructed to function properly in harsh weather conditions and conditions where salt and other corrosive materials may be used. 3.12 Ramp control signals (including mounting structure) shall meet performance specifications as defined for the region and location of deployment.
4. Travelers on the freeway need ramp meters to optimize mobility and increase the reliability of their travel times, for their trip routes that are consistent on a daily basis, such as commutes during AM and PM peak periods.	4.1. Ramp meters shall be considered at on-ramps at intervals spaced along freeway corridors to maximize travel time reliability, based on historical, current, and projected traffic demand along the corridor. 4.2. Ramp metering rates shall be determined based on proven ramp metering design parameters and traffic patterns along the corridor, to optimize mobility and maximize travel time reliability.
Operators/Operations	
5. Operators need to be able to turn the ramp meters on or off and also have the ability to override ramp meter settings remotely, in addition to on-site.	5.1. The ATMS shall include a mechanism that enables operators to interact with the ramp meter signal controllers. 5.2. Ramp Meters shall provide operators with a mechanism to activate and de-activate ramp meters both at the site of the meter and remotely. 5.3. Ramp meter signal controllers shall have the ability to receive and process commands from the ATMS. 5.4. Ramp meter signal controllers shall support remote control functions including activation/de-activation, ramp metering algorithms, and metering rates.

Need	System Requirement
	5.5. Ramp meter signal controllers shall have the ability to send data and commands to the ramp control signals, to control the devices.
6. Operators need to be able to monitor the operational status of each ramp meter from ATMS from locations remote to the ramp meters.	6.1. The ATMS shall allow users to remotely view the locations, operational status, communications status, metering rates, and any pre-set ramp metering algorithms for all ramp control signals. 6.2. The ATMS shall perform diagnostics tests of functional components of the ramp meter (field device and ramp meter signal controller), including: - Operational status - Metering rates - Communications status 6.3. Ramp meter deployments shall consider deploying nearby traffic cameras to support remote visual verification of ramp meter status. 6.4. If deployed to be operated remotely, temporary ramp meters shall respond to requests for current operational status and diagnostics. 6.5. The ATMS shall allow users to view the locations and statuses of ramp meters controlled by the software. 6.6. The ramp meter signal controllers shall have a mechanism that allows on-site viewing of current operational status and ramp metering rates.

Need	System Requirement
7. Operators/operations need ramp meters to activate and determine meter rates automatically.	7.1. Ramp meter signal controllers shall have the ability to accept real-time detailed traffic data from mainline traffic detection and ramp traffic detection. 7.2. Ramp meter signal controllers shall have the ability to communicate traffic data to the ATMS. 7.3. The ATMS shall have the ability to accept traffic data from the ramp meter signal controllers. 7.4. The ATMS shall have the ability to run algorithms that automatically activate ramp meters based on time of day/day of week. 7.5. The ATMS shall have the ability to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data. 7.6. The ATMS shall have the ability to automatically activate beacons on advanced ramp metering signs at all times that ramp metering is operational. 7.7. When local-responsive ramp metering control is deployed, the ramp meter signal controller shall have the ability to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data.

Need	System Requirement
8. Operators/operations need mechanisms to prevent the vehicles queued at ramp meters from extending into upstream lanes of traffic, either from approaching freeways, beyond the queue storage area, or from arterials where vehicles enter the on-ramp.	8.1. When needed, ramp meter deployments shall include ramp traffic detection positioned on the on-ramps at pre-determined locations, to determine when queues extend beyond the pre-designated upstream location. 8.2. Ramp traffic detection shall detect when vehicle queues at the ramp meter extend beyond the pre-defined maximum queue location and create alerts. 8.3. Ramp meter controllers shall ingest ramp traffic detection data, detect excessive queues, and adjust ramp metering rates accordingly. 8.4. The ATMS shall allow users to manually adjust ramp metering rates, as needed, in order to dissipate/flush extensive ramp queues. 8.5. When ramp meter control strategies are coordinated with nearby local traffic signal controllers, the ramp meter signal controllers shall have the ability to communicate data to local traffic signal controllers to trigger traffic signal timing updates. 8.6. When ramp meter control strategies are coordinated with a central traffic control system, the ramp meter signal controllers shall have the ability to communicate data to a central traffic signal control system as excessive queues are detected on the on-ramps. 8.7. When ramp meter control strategies are coordinated with local traffic signal controllers or a central traffic control system and ATMS, the ATMS shall have the ability to communicate excessive queue data to the local traffic signal controllers or to a central traffic control system, to trigger adjustments in traffic signal timing at nearby traffic signals.

Need	System Requirement
Administrators	
9. Administrators need to be able to configure ramp control signals, either remotely or at the ramp meter.	9.1. The ATMS shall allow administrators to add and delete ramp meters (field devices and controllers) that will be monitored and controlled by the ATMS. 9.2. The ATMS shall have a mechanism to define time of day activation parameters. 9.3. The ATMS shall have a mechanism to enter ramp meter algorithms into the ATMS. 9.4. In situations where pre-defined ramp metering rates are desired at selected ramp meters, the ATMS shall have a mechanism to pre-define these metering rates. 9.5. The ramp meters shall allow for configuration that includes connecting the ramp control signals to the ATMS software (and to any other traffic signal systems as needed) and setting ramp meter parameters such as time of day, metering rates, and queue detection parameters. 9.6. The ramp meters shall support remote configuration of the ramp meter. 9.7. The ramp meters shall support local on-site configuration of the ramp meter. 9.8. Ramp meter signal controllers shall support local cable connectivity to laptop computers running the ramp meter's manufacturer software to control activation/de-activation and ramp metering rates. 9.9. Any advanced signage with flashing beacons shall support local on-site configuration to control systems such as the ATMS or the ramp meter signal controller.

Need	System Requirement
Technicians and Installers	
10. Technicians and installers need power, communications, and support structures to be available at the site where ramp meters are deployed.	10.1. Ramp meters shall be designed and installed in accordance with requirements for roadway clearance and crashworthiness (e.g. breakaway structures or protection). 10.2. Ramp meter design shall include the approach to mounting the ramp control signal. 10.3. Ramp meter design shall include power connections. 10.4. Ramp meter design shall include components to support remote communications. 10.5. Ramp meter design shall include adequate visibility of signal indicators. 10.6. Ramp meter design shall include accessibility to the ramp control signals and the ramp meter signal controllers. 10.7. Any advanced signage that includes flashing beacons shall include power connections. 10.8. Ramp meter design shall consider whether nearby CAV roadside units (RSUs) will require direct data feeds from the ramp meter.
11. Technicians and installers need the ramp meters to adhere to appropriate safety standards, specifications, and protocols.	11.1. Ramp meters shall include temporary or permanent components to support safe lifting, transport, and installation of the ramp control signals and controller(s). 11.2. Ramp meters shall meet current ramp meter specifications as approved by MnDOT or the agency/owner that is deploying/ operating the ramp meter(s). 11.3. Ramp meter designs will include TTC plans for installing or performing field work on permanent or temporary ramp meters.

Need	System Requirement
12. Technicians and installers need the ATMS to communicate with ramp meter signal controllers and with a central traffic signal controller as available.	12.1. The ATMS shall be capable of communicating with ramp meter signal controllers. 12.2. Ramp meter signal controllers shall be capable of communicating with the ATMS. 12.3. In situations where the ATMS is communicating with a central traffic signal controller as part of a ramp metering strategy, the ATMS shall be capable of communicating with the central traffic signal controller, and vice versa.
13. Technicians and installers need ramp meter signal controllers to communicate to one another, to local traffic signal controllers, and to a central traffic signal controller.	13.1. In situations where ramp meter signal controllers are communicating with one or more local traffic signal controllers as part of ramp metering strategy, the ramp meter signal controllers and the local traffic signal controllers shall be capable of communicating with one another. 13.2. In situations where ramp meter signal controllers are communicating with a central traffic signal controller as part of a ramp metering strategy, the ramp meter signal controllers and the central traffic signal system shall be capable of communicating with one another.
CAV Infrastructure Systems and CAVs	
14. CAV infrastructure systems may need a mechanism to receive ramp meter status (e.g. activated or not activated, current metering rates).	14.1. In locations where CAV infrastructure systems broadcast messages to vehicle systems, the ramp meter signal controller shall communicate the ramp meter status (e.g. activated, de-activated, current ramp metering rate, current signal indication) to the CAV infrastructure system. Note: this data exchange will support CAV infrastructure systems in communicating the “local traveler information” information flow (roadside equipment to vehicle On-Board Equipment (OBE)). 14.2. In some situations, CAV infrastructure systems such as roadside units shall share utilities (e.g. power, communications) and structures with ramp meters.

Need	System Requirement
15. CAVs may need a mechanism to communicate directly with ramp meters.	15.1. In situations where direct ramp meter to CAVs is operational, ramp meters shall generate a message conveying the status of the ramp meter (red or green indication), in a format compatible with the two-way vehicle to roadside or cloud-based communication medium. 15.2. In situations where CAVs receive messages directly from ramp meters, the ramp meter signal display shall be visible to automated vehicle on-board cameras. 15.3. In situations where CAVs receive messages directly from ramp meters, the ramp meter signal display shall be capable of being read by machine vision systems equipped in CAVs. 15.4. In situations where CAVs or CAV infrastructure systems communicate with ramp meters, the ramp meter (or supporting roadside unit) shall receive, process, and act upon data indicating strings or platoons of vehicles and temporarily adjust metering rates.

Relationship to the National ARC-IT and Minnesota ITS Architecture

The Minnesota Statewide Regional ITS Architecture presents a vision for how ITS systems work together, share resources, and share information. The 2018 update to the ITS Architecture represents the latest status of Minnesota, as captured through outreach meetings and input from stakeholders statewide. As such, the Minnesota ITS Architecture was a valuable input to the development of this documents, supporting:

- Identification of stakeholders;
- Definition of needs for ramp metering;
- Concepts for the use of ramp metering; and
- Overall input to the requirements.

The Minnesota ITS Architecture enabled the Project Team to build upon the content of the architecture and clarify specifics for this document.

In addition to the role of supporting the development of this document, the Minnesota Statewide Regional ITS Architecture and the National Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) will continue to serve as a resource for the agencies that utilize this document as they prepare for deployment. Table 12 below identifies the needs/potential solutions included in the Minnesota ITS Architecture that are addressed through concepts for the use of ramp metering described in this document, as well as references to service packages and processes as defined in the ARC-IT. Finally, the far right column identifies the ramp metering stakeholder need(s) that were influenced or derived based on each service package.

Table 12: Summary of Local and National ITS and CAV Architecture References Mapped to Ramp Metering Needs

MN Statewide Regional ITS Architecture: Need/Potential Solutions	ARC-IT: Service Packages	ARC-IT: Processes	Ramp Metering Stakeholder Needs Influenced by each Service Package
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Process Traffic Sensor Data • Process Traffic Data • Determine Indicator State for Freeway Management • Determine Ramp State • Select Strategy	• Need 1: Reduce Conflicts with Merging Traffic • Need 2: Reduce Freeway Congestion • Need 7: Automated Ramp Meter Control • Need 8: Extensive Ramp Back-ups and Automated Adjustments
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Determine Ramp State • Output Control Data for Freeways	• Need 12: Communication to ATMS
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Provide Traffic Operations Personnel Traffic Data Interface • Select Strategy	• Need 5: Ramp Meter Control
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Process Signal Control Conflict Monitoring	• Need 3: Ramp Meter Understanding
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Monitor Roadside Equipment Operation • Collect Field Equipment Status for Repair • Collect Traffic Field Equipment Fault Data	• Need 6: Ramp Meter Monitoring • Need 12: Communication to ATMS

MN Statewide Regional ITS Architecture: Need/Potential Solutions	ARC-IT: Service Packages	ARC-IT: Processes	Ramp Metering Stakeholder Needs Influenced by each Service Package
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Provide Device Interface to Other Roadway Devices • Determine Ramp State	• Need 13: Communication Among Signal Controllers • Need 14: CAV Message Receipt
• ATMS23 Operate Ramp Meters	• TM05 Traffic Metering	• Output In-vehicle Signage Data	• Need 14: CAV Message Receipt • Need 15: CAV Local Connection
• ATMS27 Provide HOV bypass lanes at ramp meter locations	• ST06 HOV/HOT Lane Management	• Monitor HOV lane use	• Need 6: Ramp Meter Monitoring
• ATMS47 Study the potential uses of ramp meters in larger urban areas outside the Metro	• TM05 Traffic Metering	• Generate Predictive Traffic Model • Retrieve Traffic Data	• Need 1: Reduce Conflicts with Merging Traffic • Need 2: Reduce Freeway Congestion
• MCM20 Snow plow priority at traffic signals and ramp meters	• TM04 Connected Vehicle Traffic Signal System	• Manage Local Signal Priority Requests	• Need 7: Automated Ramp Meter Control • Need 15: CAV Local Connection
• MCM20 Snow plow priority at traffic signals and ramp meters	• SU01 Connected Vehicle System Monitoring and Management	• Monitor Roadside Equipment Fault Data • Manage Connected Vehicle Applications	• Need 6: Ramp Meter Monitoring • Need 14: CAV Message Receipt • Need 15: CAV Local Connection
• MCM20 Snow plow priority at traffic signals and ramp meters	• SU01 Connected Vehicle System Monitoring and Management	• Provide Field Equipment Maintenance	• Need 10: Ramp Meter Supporting Infrastructure • Need 11: Safety Standards

MN Statewide Regional ITS Architecture: Need/Potential Solutions	ARC-IT: Service Packages	ARC-IT: Processes	Ramp Metering Stakeholder Needs Influenced by each Service Package
• MCM20 Snow plow priority at traffic signals and ramp meters	• SU02 Core Authorization	• Authorize Connected Vehicle Environment Applications • Authorize Connected Vehicle Devices • Support Vehicle System Communications • Support Vehicle Secure Communications	• Need 7: Automated Ramp Meter Control • Need 14: CAV Message Receipt • Need 15: CAV Local Connection

Model Test Plan

This section presents a model test plan to support testing and validation activities during the integration and deployment stages of ramp metering to confirm that the system is developed, installed, and operating as specified by the system requirements.

Each ramp metering deployment will be different, and the testing and validation performed will likely vary depending upon the complexity of the system and the familiarity with the vendor products.

The table below provides a series of testing instructions related to the requirements presented above. The intent is that agencies using this model systems engineering document will incorporate these tests into their overall testing and validation plans, adapting them as needed.

Column 3 in the table below describes 'testing instructions' for each requirement. The ramp metering requirements include a range of requirement types and therefore the testing instructions vary. The following bullet list explains the approach to different testing instructions:

- *Advisory requirement – no testing required:* This is noted for requirements that are primarily operational advice (e.g. the locating and use of ramp metering) and therefore no formal testing is required;
- *Design:* These test instructions are used to describe testing in the form of design reviews or documentation reviews describing the ramp metering. These are typically not physical tests, but rather reviews of processes or documents;
- *Factory Acceptance Test (FAT):* These represent recommendations for FATs to allow the agency deploying the ramp metering to verify the quality assurance/quality control and ramp metering operational parameters at the site of manufacturing and assembly. This can involve the procuring agency on-site at the vendor factory testing the actual equipment to be delivered or the reports of previous tests of components, software, or features;
- *Field:* These represent recommendations for tests to be conducted in MnDOT offices or the field to test the actual deployment and functionality of the ramp metering.

Table 13: Model Test Plan for Ramp Metering

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
1.1	In locations that experience recurring unreliable travel times, permanent ramp meters shall be considered to manage the rate of flow of traffic entering freeways.	Advisory requirement – no testing required	N/A	
1.2	In situations where displacement of ramp meters occurs, such as during work zones lasting approximately the entire construction season, temporary ramp meters shall be considered to manage the rate of flow of traffic entering freeways.	Advisory requirement – no testing required	N/A	
1.3	In locations where temporary ramp configurations (e.g. during construction or maintenance activities) create situations where merging into the mainline is difficult, temporary ramp metering shall be considered to manage the speed and rate of traffic entering the freeways.	Advisory requirement – no testing required	N/A	
1.4	Ramp meters shall be located strategically along freeway corridors to enhance freeway traffic management and travelers' merging experience.	Advisory requirement – no testing required	N/A	
1.5	Ramp meter deployments should consider MUTCD requirements during design and placement.	Design – Confirm that the design is in compliance with the MUTCD. Field – Confirm that ramp meters are placed along on-ramps in compliance with the MUTCD.	Design - Content Review Field - Pass/Fail	
2.1	Ramp meters shall be located at on-ramps at intervals spaced along freeway corridors to minimize freeway congestion and merging conflicts, based on historical,	Design – Confirm ramp meters are located at on-ramps at intervals spaced along freeway corridors to minimize freeway congestion and merging conflicts, based on	Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
	current, and projected traffic demand along the corridor.	historical, current, and projected traffic demand along the corridor.		
2.2	Ramp metering rates shall be determined based on proven ramp metering design parameters and traffic patterns along the corridor, to minimize congestion along the corridor and to minimize merging conflicts.	Design – Confirm that ramp meter rates are based on proven design parameters and traffic patterns in the corridor. Field – Confirm that the ramp meter rates are based on proven design parameters and traffic patterns in the corridor to minimize both congestion along the corridor and merging conflicts.	Design - Content Review Field - Pass/Fail	
3.1	Ramp control signals shall be located for visibility from the full width of the on-ramp.	Design – Confirm that the design includes adequate visibility of ramp control signals from the full width of the on-ramp. Field – Confirm that the ramp control signals are visible from the full width of the on-ramp.	Design - Content Review Field - Pass/Fail	
3.2	Ramp control signals shall be located so the signals are visible from a distance that is appropriate for the on-ramp on which it is installed, considering the local speed limit and sight distance.	Design – Confirm that the design includes adequate visibility of ramp control signals from an appropriate distance on the on-ramp given local speed limit and sight distance. Field – Confirm that the ramp control signals are visible from an appropriate distance on the on-ramp given local speed limit and sight distance.	Design - Content Review Field - Pass/Fail	
3.3	At each ramp meter location, one ramp control signal shall be placed on both sides of the on-ramp, adjacent to one another.	Design – Confirm that the design includes a ramp control signals on each side of the on-ramp, adjacent to one another.	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		Field – Confirm that a ramp control signal is on each side of the on-ramp, adjacent to one another.	Field - Pass/Fail	
3.4	When ramp meters are placed at on-ramps where approaching traffic is entering from a high-speed freeway or where sight distance is limited, signage shall be placed in advance of the ramp meter, indicating that a ramp meter is ahead or that a ramp meter is activated when the sign's beacons are flashing.	Design – Confirm that the design includes signage to indicate a downstream ramp meter in advance of the ramp meter, as appropriate for the location. Field – Confirm that signage to indicate a downstream ramp meter in advance of the ramp meter is appropriate for the location.	Design - Content Review Field - Pass/Fail	
3.5	Signage shall be placed in advance of the ramp meter indicating form two lanes when metered.	Design – Confirm that the design includes signage in advance of the ramp meter indicating form two lanes when metered. Field – Confirm that signage is placed in advance of the ramp meter indicating form two lanes when metered.	Design - Content Review Field - Pass/Fail	
3.6	Signage shall be placed at the ramp control signal to indicate stop here on red.	Design – Confirm that the design includes signage at the ramp meter indicating stop here on red. Field – Confirm that signage is placed at the ramp meter indicating stop here on red.	Design - Content Review Field - Pass/Fail	
3.7	Signage shall be placed at the ramp control signal to indicate one car on green.	Design – Confirm that the design includes signage at the ramp meter indicating one car on green. Field – Confirm that signage is placed at the ramp meter indicating one car on green.	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
3.8	All signage for ramp meter deployments shall be designed and placed in compliance with the MUTCD.	Design – Confirm that the design for signage is in compliance with the MUTCD. Field – Confirm that ramp meter signage is placed in compliance with the MUTCD.	Design - Content Review Field - Pass/Fail	
3.9	Ramp control signals and all associated field components shall have the ability to perform in extreme cold conditions experienced in Minnesota.	FAT – Confirm that a cold test was performed on the ramp control signals and all associated field components.	Pass/Fail	
3.10	Ramp control signals and all associated field components shall function properly in extreme heat conditions.	FAT – Confirm that a heat test was performed on the ramp control signals and all associated field components.	Pass/Fail	
3.11	Ramp control signals and all associated field components shall be constructed to function properly in harsh weather conditions and conditions where salt and other corrosive materials may be used.	Design – Confirm that the housing and exterior components are made from materials resistant to corrosion. FAT – Confirm that exterior seams are continuously welded with no gaps. FAT – Confirm that exterior welds are free of cracks, blowholes, and irregularities.	Design - Content Review FAT - Pass/Fail	
3.12	Ramp control signals (including mounting structure) shall meet performance specifications as defined for the region and location of deployment.	Design – Confirm that design has been completed for ramp control signals and mounting structure to meet local performance specifications. FAT – Confirm that ramp control signals meet local specifications. Field – Confirm ramp control signals and mounting structure is installed and operational per local performance	Design - Pass/Fail FAT - Pass/Fail Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		specifications and is documented with supporting illustrations and figures.		
4.1	Ramp meters shall be considered at on-ramps at intervals spaced along freeway corridors to maximize travel time reliability, based on historical, current, and projected traffic demand along the corridor.	Design – Confirm ramp meters have been considered at on-ramps at intervals spaced along freeway corridors to minimize freeway congestion and merging conflicts, based on historical, current, and projected traffic demand along the corridor.	Content Review	
4.2	Ramp metering rates shall be determined based on proven ramp metering design parameters and traffic patterns along the corridor, to optimize mobility and maximize travel time reliability.	Design – Confirm that ramp meter rates are based on proven design parameters and traffic patterns in the corridor. Field – Confirm that the ramp meter rates are based on proven design parameters and traffic patterns in the corridor to minimize both congestion along the corridor and merging conflicts.	Design - Content Review Field - Pass/Fail	
5.1	The ATMS shall include a mechanism that enables operators to interact with the ramp meter signal controllers.	Design – Confirm the design includes a mechanism allowing operators to interact with the ramp meter signal controllers via the ATMS. Field – Confirm that operators can use the ATMS to interact with the ramp meter signal controllers.	Design - Content Review Field - Pass/Fail	
5.2	15.5. Ramp Meters shall provide operators with a mechanism to activate and de-activate ramp meters both at the site of the meter and remotely.	Design – Confirm the design includes a mechanism allowing operators to activate and de-activate ramp meters using the ATMS or in the field at the ramp meter. Field – Confirm that an operator in the field can activate and de-activate ramp meters.	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		Field – Confirm that an operator can activate and de-activate ramp meters from remotely.		
5.3	Ramp meter signal controllers shall have the ability to receive and process commands from the ATMS.	Design – Confirm the design allows ramp meter signal controllers to receive and process commands from the ATMS. Field – Confirm that ramp meter signal controllers can receive and process commands from the ATMS.	Design - Content Review Field - Pass/Fail	
5.4	Ramp meter signal controllers shall support remote control functions including activation/de-activation, ramp metering algorithms, and metering rates.	Design – Confirm the design supports remote control functions for the ramp meter signal controllers that include activation/de-activation, ramp metering algorithms, and metering rates. Field – Confirm that ramp meter signal controllers support remote control functions including activation/de-activation, ramp metering algorithms, and metering rates.	Design - Content Review Field - Pass/Fail	
5.5	Ramp meter signal controllers shall have the ability to send data and commands to the ramp control signals, to control the devices.	Design – Confirm the design allows ramp meter signal controllers to send data and commands to the ramp control signals, to control the devices. Field – Confirm that ramp meter signal controllers can send data and commands to the ramp control signals, to control the devices.	Design - Content Review Field - Pass/Fail	
6.1	The ATMS shall allow users to remotely view the locations, operational status,	Design – Confirm the design includes a mechanism in the ATMS that allows users	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
	communications status, metering rates, and any pre-set ramp metering algorithms for all ramp control signals.	to remotely view the locations, operational status, communications status, metering rates, and any pre-set ramp metering algorithms for all ramp control signals. Field – Confirm that users can remotely view the locations, operational status, communications status, metering rates, and any pre-set ramp metering algorithms for all ramp control signals in the ATMS.	Field - Pass/Fail	
6.2	The ATMS shall perform diagnostics tests of functional components of the ramp meter (field device and ramp meter signal controller), including: – Operational status – Metering rates – Communications status	Design – Confirm the design allows the ATMS to perform diagnostics tests of functional components of the ramp meter, including operational status, metering rates, and communications status. Field – Confirm that the ATMS can perform diagnostics tests of functional components of the ramp meter, including operational status, metering rates, and communications status.	Design - Content Review Field - Pass/Fail	
6.3	Ramp meter deployments shall consider deploying nearby traffic cameras to support remote visual verification of ramp meter status.	Advisory requirement – no testing required	N/A	
6.4	If deployed to be operated remotely, temporary ramp meters shall respond to requests for current operational status and diagnostics.	Design – Confirm the design includes a mechanism to allow temporary ramp meters to respond to requests for current operational status and diagnostics, if deployed to be operated remotely.	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		Field – Confirm temporary ramp meters can respond to requests for current operational status and diagnostics, if deployed to be operated remotely.	Field - Pass/Fail	
6.5	The ATMS shall allow users to view the locations and statuses of ramp meters controlled by the software.	Design – Confirm the design includes a mechanism in the ATMS for users to view the locations and statuses of ramp meters controlled by the software. Field – Confirm that users can view the locations and statuses of ramp meters controlled by the software in the ATMS.	Design - Content Review Field - Pass/Fail	
6.6	The ramp meter signal controllers shall have a mechanism that allows on-site viewing of current operational status and ramp metering rates.	Design – Confirm the ramp meter signal controller design includes a mechanism that allows on-site viewing of current operational status and ramp metering rates. Field – Confirm availability of on-site viewing of current operational status and ramp metering rates.	Design - Content Review Field - Pass/Fail	
7.1	Ramp meter signal controllers shall have the ability to accept real-time detailed traffic data from mainline traffic detection and ramp traffic detection.	Design – Confirm the ramp meter signal controller design include the ability to accept real-time detailed traffic data from mainline traffic detection and ramp traffic detection. Field – Confirm ramp meter signal controller can accept real-time detailed traffic data from mainline traffic detection and ramp traffic detection.	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
7.2	Ramp meter signal controllers shall have the ability to communicate traffic data to the ATMS.	Design – Confirm the ramp meter signal controller design includes a mechanism to communicate traffic data to the ATMS. Field – Confirm the ramp meter signal controllers can communicate traffic data to the ATMS.	Design - Content Review Field - Pass/Fail	
7.3	The ATMS shall have the ability to accept traffic data from the ramp meter signal controllers.	Design – Confirm the design includes a mechanism for the ATMS to accept traffic data from the ramp meter signal controllers. Field – Confirm the ATMS can accept traffic data from the ramp meter signal controllers.	Design - Content Review Field - Pass/Fail	
7.4	The ATMS shall have the ability to run algorithms that automatically activate ramp meters based on time of day/day of week.	Design – Confirm the design includes a mechanism for the ATMS to run algorithms that automatically activate ramp meters based on time of day/day of week. Field – Confirm the ATMS can run algorithms that automatically activate ramp meters based on time of day/day of week.	Design - Content Review Field - Pass/Fail	
7.5	The ATMS shall have the ability to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data.	Design – Confirm the design includes a mechanism for the ATMS to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data. Field – Confirm the ATMS can run algorithms that automatically adjust ramp	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		metering rates, based on real-time traffic data.		
7.6	The ATMS shall have the ability to automatically activate beacons on advanced ramp metering signs at all times that ramp metering is operational.	Design – Confirm the design includes a mechanism for the ATMS to automatically activate beacons on advanced ramp metering signs at all times that ramp metering is operational. Field – Confirm the ATMS can automatically activate beacons on advanced ramp metering signs at all times that ramp metering is operational.	Design - Content Review Field - Pass/Fail	
7.7	When local-responsive ramp metering control is deployed, the ramp meter signal controller shall have the ability to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data.	Design – Confirm the design allows the ramp meter signal controller to run algorithms that automatically adjust ramp metering rates, based on real-time traffic data, as applicable. Field – Confirm the ramp meter signal controller can run algorithms that automatically adjust ramp metering rates, based on real-time traffic data, as applicable.	Design - Content Review Field - Pass/Fail	
8.1	When needed, ramp meter deployments shall include ramp traffic detection positioned on the on-ramps at pre-determined locations, to determine when queues extend beyond the pre-designated upstream location.	Design – Confirm the design includes ramp traffic detection at a pre-defined maximum queue location to detect queues, as needed. Field – Confirm the ramp traffic detection is installed at the pre-defined maximum queue location, as needed.	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
8.2	Ramp traffic detection shall detect when vehicle queues at the ramp meter extend beyond the pre-defined maximum queue location and create alerts.	Design – Confirm the design includes ramp traffic detection at a pre-defined maximum queue location to create alerts. Field – Confirm the ramp traffic detection is installed at the pre-defined maximum queue location and can create alerts.	Design - Content Review Field - Pass/Fail	
8.3	When local-responsive ramp metering is deployed, ramp meter controllers shall ingest ramp traffic detection data, detect excessive queues, and adjust ramp metering rates accordingly.	Design – Confirm the design allows ramp meter controllers to ingest ramp traffic detection data, detect excessive queues, and adjust ramp metering rates accordingly, if applicable. Field – Confirm that ramp meter controllers ingest ramp traffic detection data, detect excessive queues, and adjust ramp metering rates accordingly, if applicable.	Design - Content Review Field - Pass/Fail	
8.4	The ATMS shall allow users to manually adjust ramp metering rates, as needed, in order to dissipate/flush extensive ramp queues.	Design – Confirm the design includes a mechanism in the ATMS for users to manually adjust ramp metering rates, as needed. Field – Confirm the ATMS allows users to manually adjust ramp metering rates, as needed.	Design - Content Review Field - Pass/Fail	
8.5	When ramp meter control strategies are coordinated with nearby local traffic signal controllers, the ramp meter signal controllers shall have the ability to communicate data to local traffic signal	Design – Confirm the design includes a communication mechanism that allows the ramp meter signal controllers to communicate data to the local traffic signal controllers, if applicable.	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
	controllers to trigger traffic signal timing updates.	Field – Confirm that the ramp meter signal controllers can communicate data to the local traffic signal controllers to trigger traffic signal timing updates, if applicable.	Field - Pass/Fail	
8.6	When ramp meter control strategies are coordinated with a central traffic control system, the ramp meter signal controllers shall have the ability to communicate data to a central traffic signal control system as excessive queues are detected on the on-ramps.	Design – Confirm the design includes a communication mechanism that allows the ramp meter signal controllers to communicate data to the central traffic control system, if applicable. Field – Confirm that the ramp meter signal controllers communicates data to the central traffic control system as excessive queues are detected on the on-ramps, if applicable.	Design - Content Review Field - Pass/Fail	
8.7	When ramp meter control strategies are coordinated with local traffic signal controllers or a central traffic control system and ATMS, the ATMS shall have the ability to communicate excessive queue data to the local traffic signal controllers or to a central traffic control system, to trigger adjustments in traffic signal timing at nearby traffic signals.	Design – Confirm the design includes a communication mechanism that allows the ATMS to communicate excessive queue data to the local traffic signal controllers or to a central traffic control system, if applicable. Field – Confirm that the ATMS can communicate with the excessive queue data to the local traffic signal controllers or to a central traffic control system, if applicable.	Design - Content Review Field - Pass/Fail	
9.1	The ATMS shall allow administrators to add and delete ramp meters (field devices and controllers) that will be monitored and controlled by the ATMS.	Design – Confirm that the design allows administrators to add and delete ramp meters that will be monitored and controlled by the ATMS.	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		Field – Confirm that administrators can add and delete ramp meters that are monitored and controlled by the ATMS.	Field - Pass/Fail	
9.2	The ATMS shall have a mechanism to define time of day activation parameters	Design – Confirm that the ATMS allows administrators to define start and stop time of day parameters for ramp meter control. Field – Confirm that time of day parameters for ramp meter control operate and turn ramp meters on and off at the appropriate times/days.	Design - Content Review Field - Pass/Fail	
9.3	The ATMS shall have a mechanism to enter ramp meter algorithms into the ATMS.	Design – Confirm the ATMS design includes a mechanism for users to enter ramp meter algorithms into the ATMS. Field – Confirm that algorithms in the ATMS determine ramp meter timing parameters as designed in the algorithm, considering real-time traffic data.	Design - Content Review Field - Pass/Fail	
9.4	In situations where pre-defined ramp metering rates are desired at selected ramp meters, the ATMS shall have a mechanism to pre-define these metering rates.	Design – Confirm the design includes a mechanism for the ATMS that allows operators to pre-define metering rates, as applicable. Field – Confirm that the pre-defined metering rates in the ATMS are communicated to the ramp meter and the rates are as designated.	Design - Content Review Field - Pass/Fail	
9.5	The ramp meters shall allow for configuration that includes connecting the ramp control signals to the ATMS software (and to any other traffic signal systems as	Design – Confirm that the ATMS design includes connectivity to the ramp meters. Design – Confirm the ramp meters deployed include connectivity to the ATMS.	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
	needed) and setting ramp meter parameters such as time of day, metering rates, and queue detection parameters.	Field – Confirm that a ramp meter can be added to the ATMS, and once added that operators can view the ramp meter status and manually turn the ramp meter on and off.	Field - Pass/Fail	
9.6	The ramp meters shall support remote configuration of the ramp meter.	Design – Confirm that the design allows the ramp meter to be configured remotely. Field – Confirm that the ramp meter can be configured remotely.	Design - Content Review Field - Pass/Fail	
9.7	The ramp meters shall support local on-site configuration of the ramp meter.	Design – Confirm that the design allows the ramp meter to be configured locally on-site. Field – Confirm that the ramp meter can be configured locally on-site.	Design - Content Review Field - Pass/Fail	
9.8	Ramp meter signal controllers shall support local cable connectivity to laptop computers running the ramp meter's manufacturer software to control activation/de-activation and ramp metering rates.	Design – Confirm that the design supports the ramp meter signal controllers to be locally connected to laptop computers running the ramp meter's manufacturer software to control activation/de-activation and ramp metering rates. Field – Confirm that the ramp meter signal controllers support local cable connectivity to laptop computers running the ramp meter's manufacturer software to control activation/de-activation and ramp metering rates.	Design - Content Review Field - Pass/Fail	
9.9	Any advanced signage with flashing beacons shall support local on-site configuration to	Design – Confirm that the design allows any advanced signage with flashing beacons to	Design - Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
	control systems such as the ATMS or the ramp meter signal controller.	be configured locally on-site with control systems. Field – Confirm that any advanced signage with flashing beacons can be configured locally on-site with control systems.	 Field - Pass/Fail	
10.1	Ramp meters shall be designed and installed in accordance with requirements for roadway clearance and crashworthiness (e.g. breakaway structures or protection).	Design – Confirm that the ramp meter design meets current requirements for roadway clearance and crashworthiness. FAT – Confirm that ramp meter equipment meets current requirements for crashworthiness. Field – Confirm that ramp meter design meets current requirements for roadway clearance and crashworthiness.	Design - Content Review FAT - Pass/Fail Field - Pass/Fail	
10.2	Ramp meter design shall include the approach to mounting the ramp control signal.	Design – Confirm that the design includes the approach for mounting the ramp control signal.	Content Review	
10.3	Ramp meter design shall include power connections.	Design – Confirm that the design includes power connections.	Content Review	
10.4	Ramp meter design shall include components to support remote communications.	Design – Confirm that the design includes components to support remote communications.	Content Review	
10.5	Ramp meter design shall include adequate visibility of signal indicators.	Design – Confirm that the design includes adequate visibility of signal indicators.	Content Review	
10.6	Ramp meter design shall include accessibility to the ramp control signals and the ramp meter signal controllers.	Design – Confirm that the design includes accessibility to the ramp control signals and the ramp meter signal controllers.	Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
10.7	Any advanced signage that includes flashing beacons shall include power connections.	Design – Confirm that the design includes power connections, when advanced signage with flashing beacons is included. Field – Confirm that power connections, when advanced signage with flashing beacons is present.	Design - Content Review Field - Pass/Fail	
10.8	Ramp meter design shall consider whether nearby CAV RSUs will require direct data feeds from the ramp meter.	Design – Confirm that the design considers whether nearby CAV RSUs require direct data feeds from the ramp meter.	Content Review	
11.1	Ramp meters shall include temporary or permanent components to support safe lifting, transport, and installation of the ramp control signals and controller(s).	Design – Confirm that the design includes safety components to support lifting, transport, and installation of ramp meter equipment. FAT – Confirm that safety components are sufficient for lifting, transport, and installation.	Design - Content Review FAT - Pass/Fail	
11.2	Ramp meters shall meet current ramp meter specifications as approved by MnDOT or the agency/owner that is deploying/operating the ramp meter(s).	Design – Confirm that the design meets current ramp meter specifications as approved by the appropriate agency. FAT – Confirm that the ramp meters meet local specifications. Field – Confirm that the ramp meters meet current ramp meter specifications.	Pass/Fail	
11.3	Ramp meter designs will include TTC plans for installing or performing field work on permanent or temporary ramp meters.	Design – Confirm that the design includes TTC plans.	Content Review	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
12.1	The ATMS shall be capable of communicating with ramp meter signal controllers.	Design – Confirm the design includes a communication mechanism between the ramp meter signal controllers and ATMS. Field – Confirm that the ATMS can communicate with the ramp meter signal controllers.	Design - Content Review Field - Pass/Fail	
12.2	Ramp meter signal controllers shall be capable of communicating with the ATMS.	Design – Confirm the design includes a communication mechanism between the ramp meter signal controllers and ATMS. Field – Confirm that the ramp meter signal controllers can communicate with the ATMS.	Design - Content Review Field - Pass/Fail	
12.3	In situations where the ATMS is communicating with a central traffic signal controller as part of a ramp metering strategy, the ATMS shall be capable of communicating with the central traffic signal controller, and vice versa.	Design – Confirm the design includes a communication mechanism between the central traffic signal controller and ATMS, when applicable. Field – Confirm that the ATMS and central traffic signal controller can communicate with each other.	Design - Content Review Field - Pass/Fail	
13.1	In situations where ramp meter signal controllers are communicating with one or more local traffic signal controllers as part of ramp metering strategy, the ramp meter signal controllers and the local traffic signal controllers shall be capable of communicating with one another.	Design – Confirm the design includes a communication mechanism between the ramp meter signal controllers and local traffic signal controllers. Field – Confirm that the ramp meter signal controllers and the local traffic signal controllers are communicating with one another.	Design - Content Review Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
13.2	In situations where ramp meter signal controllers are communicating with a central traffic signal controller as part of a ramp metering strategy, the ramp meter signal controllers and the central traffic signal system shall be capable of communicating with one another.	Design – Confirm the design includes a communication mechanism between the ramp meter signal controllers and central traffic signal controller. Field – Confirm that the ramp meter signal controllers and the central traffic signal controllers are communicating with one another.	Design - Content Review Field - Pass/Fail	
14.1	In locations where CAV infrastructure systems broadcast messages to vehicle systems, the ramp meter signal controller shall communicate the ramp meter status (e.g. activated, de-activated, current ramp metering rate, current signal indication) to the CAV infrastructure system. Note: this data exchange will support CAV infrastructure systems in communicating the "local traveler information" information flow (roadside equipment to vehicle OBE).	Design – Confirm CAV message generation capabilities. Field – Demonstration of ramp meter signal controller ability to generate a CAV message in a standard format that conveys the ramp meter status.	Design - Content Review Field - Pass/Fail	
14.2	In some situations, CAV infrastructure systems such as roadside units shall share utilities (e.g. power, communications) and structures with ramp meters.	Advisory requirement – no testing required	N/A	
15.1	In situations where direct ramp meter to CAVs is operational, ramp meters shall generate a message conveying the status of the ramp meter (red or green indication), in a format compatible with the two-way vehicle to roadside or cloud-based communication medium.	Design – Confirm CAV communications and processing capabilities. FAT – Demonstration of ramp meter ability to: • Generate a CAV message in a standard format that conveys the ramp meter status.	Design - Content Review FAT - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		• Communicate the generated CAV message to vehicles in a format compatible with standard communications mediums. Field – Confirm with one or more on-board devices that the ramp meter is able to: • Generate a CAV message in a standard format that conveys the ramp meter status. • Communicate the generated CAV message to equipped vehicle systems via one or more standard communications mechanisms.	Field - Pass/Fail	
15.2	In situations where CAVs receive messages directly from ramp meters, the ramp meter signal display shall be visible to automated vehicle on-board cameras.	Design - Confirm that design documents describing ramp meter placement address the visibility of the signal display to automated vehicle on-board cameras.	Content Review	
15.3	In situations where CAVs receive messages directly from ramp meters, the ramp meter signal display shall be capable of being read by machine vision systems equipped in CAVs.	FAT - Confirm that the ramp meter displays are capable of being read by machine vision systems equipped in CAVs. Field – After installation, drive in each lane of the on-ramp to confirm that signal display(s) are capable of being read by machine vision systems equipped in CAVs.	Pass/Fail	
15.4	In situations where CAVs or CAV infrastructure systems communicate with ramp meters, the ramp meter (or supporting roadside unit) shall receive, process, and act upon data indicating strings or platoons of vehicles and temporarily adjust metering rates.	Design – Confirm ramp meter or supporting roadside unit CAV communications and processing capabilities. FAT – Demonstration of ramp meter or supporting roadside unit:	Design - Content Review FAT - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments/ Notes
		• Receiving CAV messages in standard formats. • Processing and retaining multiple CAV messages to parse out various data elements. • Acting on received CAV messages, e.g. communicating summary data to MnDOT or temporarily adjusting metering rates. Field – Confirm with one or more on-board devices that the ramp meter or supporting roadside unit is able to: • Receive CAV messages in standard formats. • Process and retain multiple CAV messages. • Act on received CAV messages, e.g. communicating summary data to MnDOT or temporarily adjusting metering rates.	Field - Pass/Fail	