DEPARTMENT OF TRANSPORTATION

Model Systems Engineering Document

ITS Application: Dynamic Curve Warning

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Contents

Acronyms

ARC-IT	•	National Architecture Reference for Cooperative and Intelligent Transportation
ATMS	•	Advanced Traffic Management Software
BSM	•	Basic Safety Message
CARS	•	Condition Acquisition Reporting System
CAV	•	Connected and Automated Vehicle
DMS	•	Dynamic Message Signs
EDCM	•	Event Driven Configurable Messages
FAT	•	Factory Acceptance Test
IRIS	•	Intelligent Roadway Information System
ITS	•	Intelligent Transportation System
LAN	•	Local Area Network
MUTCD	•	Manual on Uniform Traffic Control Devices (MUTCD)
MnDOT	•	Minnesota Department of Transportation
NTCIP	•	National Transportation Communications for ITS Protocol
RSU	•	Roadside Unit
RSM	•	Road Safety Messages
RTMC	•	Regional Transportation Management Center
SDCWS	•	Sequential Dynamic Curve Warning System
SEA	•	Systems Engineering Analysis
TAMS	•	Transportation Asset Management System
TTC	•	Temporary Traffic Control
VPN	•	Virtual Private Network
WAN	•	Wide Area Network
WIM	•	Weigh-in-Motion

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 dynamic curve warning systems. The content of this document will be a systems engineering analysis resource to support project compliance as set forth in Federal Regulation 23 CFR Section 940 (Rule 940: Intelligent Transportation Systems (ITS) Architecture and Standards). This document can be used in conjunction with the MnDOT Statewide Regional ITS Architecture and related 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 – Dynamic Curve Warning

Transportation agencies sometimes deploy dynamic curve warning systems in advance of horizontal roadway curves, especially in advance of horizontal curves at locations that have a history of more than typical crashes such as lane departure crashes or rollover crashes. Prior to deploying dynamic curve warning systems, other strategies to reduce crashes at candidate locations should be tried (e.g. geometric improvement, operational improvement, static warning signs, etc.). In addition, deployment guidance and consideration should also be in compliance with the Minnesota Manual on Uniform Traffic Control Device (MUTCD) and other applicable standards and engineering practices.

Dynamic curve warning systems detect vehicle speeds approaching a horizontal curve and activate advanced warning signs to alert drivers if the vehicle speed exceeds the curve threshold speed (i.e. curve advisory speed or another speed determined by the agency) for maneuvering the curve. In some cases, additional vehicle detection data such as vehicle height, length, weight, axle spacing, or lane position may be deployed to provide truck (or high-profile vehicle) rollover warnings to drivers.

As operations of Connected and Automated Vehicles (CAVs) expand, several data exchanges between CAV management systems and CAVs are anticipated, some of which will utilize vehicle position data in combination with the infrastructure systems to alert CAV-equipped vehicles of conditions ahead. Functions of dynamic curve warning systems may be completed by field devices as a stand-alone system or in conjunction with a supporting operator using Advanced Traffic Management Software (ATMS), if a communications connection to the ATMS is present.

Dynamic Curve Warning Environment/Components

Table 1 presents core components and optional components that would comprise the environment for a dynamic curve warning system, along with corresponding functions of each.

Table 1: Dynamic Curve Warning Environment/Components with Corresponding Function

Environment/Component	Function
Core Components of Dynamic Curve Warning System	
1. Speed Detection	Field detection sensors that detect the speed of vehicles approaching a horizontal curve. The detected vehicle speed is compared to a pre-determined curve threshold speed to trigger activation of a warning sign. These detection devices may be placed for lane-specific detection, as needed, for lane-specific warnings. Additional, optional traffic detection such as vehicle height or length detection devices or weigh-in-motion (WIM) sensors may be used to supplement speed detection data for dynamic curve warning systems that include truck rollover warnings (see *Optional Components* in this table).
2. Processing and/or Communications	For stand-alone dynamic curve warning systems, this is the connection between speed detection and the warning signs. In situations where there is connectivity to the ATMS, this component processes data from speed detection and/or the warning signs (as the dynamic curve warning system is activated or de-activated) and sends it to the ATMS. As vehicles approach the horizontal curve, this component compares vehicle speeds from the speed detection to a pre-determined curve threshold speed and activates warning signs if the vehicle speed exceeds the pre-determined curve threshold speed. The processing and communications component could be a stand-alone unit or could be incorporated into the warning signs or into the speed detection mechanism, depending upon local design.
3. Warning Signs	Visual indicators to travelers that they are approaching a horizontal curve traveling at a speed that is higher than the curve threshold speed for the horizontal curve ahead. Warning signs could include static signs with flashing beacons, blinking chevrons, blank-out signs that display one message when activated or no message when not activated, or Dynamic Message Signs (DMS). Warning signs will activate when the speed of an approaching vehicle exceeds a pre-determined curve threshold speed. The number of signs, sign locations, and sign types may vary for each system deployment, based on local conditions. See Table 2 for examples of warning signs.

Environment/Component	Function
Optional Components of Dynamic Curve Warning System	
4. Height Detection, Length Detection, and/or Weigh-in-Motion Sensors	Field detection devices that detect vehicle characteristics such as vehicle height, length, weight, or axle spacing, used in combination with speed detection to identify vehicles that would trigger warning signs at different speeds than typical vehicles. These vehicle classification detection devices may be placed for lane-specific detection, as needed, for lane-specific warnings.
5. Optional Speed Detection	Optional speed data from traffic detection at various locations (i.e. in advance of warning signs, between the warning sign and the curve, and/or along the curve section) that may be used to detect changes in vehicle speed in reaction to sign activations.
6. Video	Cameras placed to enable operators to view operability of warning signs and/or traffic conditions near the dynamic curve warning system. Cameras may convey still images or live video. *(See MnDOT Model Systems Engineering Document, ITS Application: Video).*
7. Communications to ATMS	The communications infrastructure to allow data communications between the local dynamic curve warning system and the ATMS. Note that there are situations where dynamic curve warning systems exist as stand-alone systems and are not connected to the ATMS.
8. ATMS	The software that is used by operations personnel to monitor traffic conditions and infrastructure systems. For example, the ATMS may enable users to view video at the site of the dynamic curve warning system, view data describing system activations and traffic detection data (e.g. speeds, vehicle heights), or poll field devices for operability issues. The ATMS may also log system activations. The ATMS would not remotely activate specific displays of warnings.
9. Electrical Current Sensing Device	A device that detects the flow of electrical current to the dynamic curve warning system’s field devices (e.g. speed detection field sensors, warning signs) to assist with monitoring operability of the system. Electrical current sensing devices may connect to the ATMS to assess system activations from a remote location.
10. Traveler Information Systems	Agency traveler information systems that may access digital roadway geometry information from the ATMS (e.g. threshold speeds for curves) and provide relevant information, including dynamic curve warnings, to travelers (e.g. via the “tell me” feature in an agency mobile app) or to external entities such third-party information providers.

Environment/Component	Function
11. Roadside Unit (RSU)	A field device used to communicate with CAVs. RSUs may be used to broadcast messages to CAVs about curve advisory speeds, locations of horizontal curves ahead, and/or may receive messages broadcast from vehicles (e.g. Basic Safety Message (BSM)) to receive data from vehicles that may describe vehicle speeds or other vehicle parameters such as acceleration/deceleration rates. RSUs may assemble needed security credentials for messages, if required.
12. CAV Infrastructure Systems	The systems deployed by DOTs to communicate with on-board units within CAVs. Dynamic curve warning systems (or the ATMS) may communicate curve warning information to CAV Infrastructure Systems to pass on to CAVs. Similarly, CAVs may broadcast vehicle information (e.g. speed, acceleration, heading) and this information may be received by the CAV Infrastructure Systems. CAV Infrastructure Systems may include communications to onboard units in vehicles using RSUs, internet cloud connectivity, or network cellular connection.
13. CAVs	The vehicles and on-board applications that communicate with CAV Infrastructure Systems and other CAVs. As noted in this document, situations may exist where CAVs may receive curve warning notices and alert drivers. CAVs may also be a source of information for other CAVs and the infrastructure.

A dynamic curve warning system could be either a stand-alone system that operates locally in in the field (with no communication connection to the ATMS) or could be connected to the ATMS for additional monitoring. The provision of a connection from a dynamic curve warning system to the ATMS is a local decision to be addressed during the design process. This decision is expected to be based on a variety of factors that determine whether local conditions warrant remote automated system notifications. These factors include the location of the roadway within the larger transportation network, potential impact of the recurring dynamic curve warnings, number of travelers impacted, and availability and cost to provide communications to the ATMS.

Figure 1 illustrates the connections between components and related systems/users of a stand-alone dynamic curve warning system. Figure 2 illustrates a dynamic curve warning system that is connected to the ATMS.

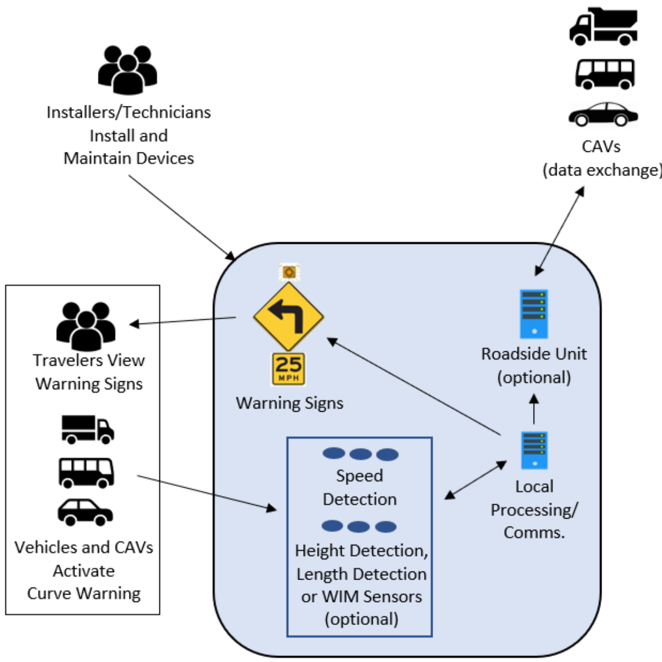


Figure 1: Illustration of Stand-Alone Dynamic Curve Warning System - Components and Related Systems/Users

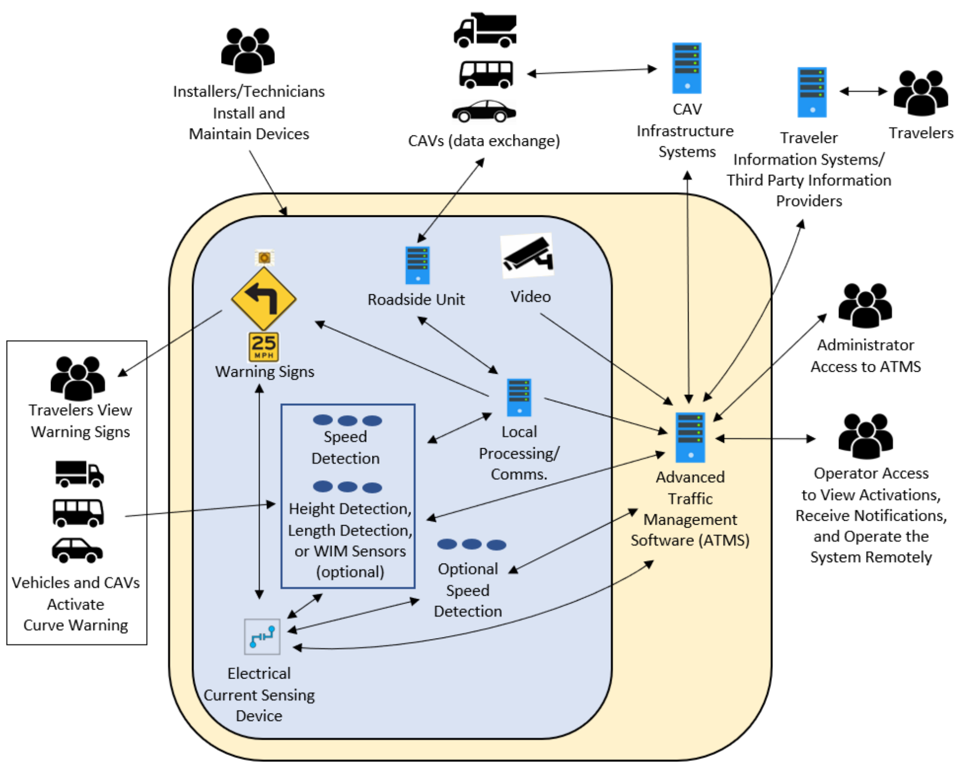
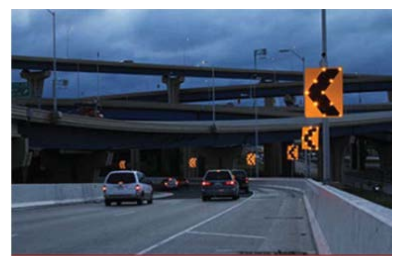


Figure 2: Illustration of Dynamic Curve Warning System Connected to ATMS - Components and Related Systems/Users

Examples of Warning Signs for Dynamic Curve Warning

Table 2 provides examples of warning signs that may be included in dynamic curve warning systems.

Table 2: Examples of Warning Signs for Dynamic Curve Warning

Warning Sign Type	*Description*	*Photos/Graphics**
Static Signs with Flashing Beacons	Static signs with attached beacon(s) that begin to flash when speed detection indicates that the vehicle approaching a horizontal curve exceeds a pre-determined curve threshold speed. The beacon(s) stop flashing at a pre-determined time following activation.	
Speed Indicator Signs	Signs that display the speed of the approaching vehicle, to increase drivers' awareness of their current speed as they approach a horizontal curve. Speed indicator signs are often mounted with a sign indicating the curve advisory speed, allowing drivers to view their speed in relation to the advisory speed, prior to reaching the horizontal curve.	
Sequential Dynamic Curve Warning Systems[1]	Sequential dynamic curve warning systems (SDCWS) have been implemented as a means to reduce vehicle operating speeds and improve curve delineation. SDCWS include horizontal curve chevron signs with solar powered flashing lights embedded in the sign. SDCWS often include advanced warning signs (e.g. static signs with flashing beacons or DMS) in combination with horizontal curve chevron signs, to provide both advanced warning and to guide drivers through the upcoming horizontal curve.	 *Source: FHWA (2016)*[2]
Blank-out Signs/ DMS	Signs that that display advisory messages based on conditions ahead. Blank-out signs display pre-determined messages that are automatically posted and removed based on pre-determined parameters (e.g. curve threshold speeds, vehicle height, length or weight) DMS may have capability for unique messages to be posted by operators. (See *MnDOT Model Systems Engineering Document, ITS Application: Dynamic Message Signs*.)	

**The example graphics shown in this table are for illustrative purposes only, to help demonstrate the system concept described in this document. Sign types and messages will be determined during design of the dynamic curve warning system.*

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[1] Smadi et al. *Evaluation of the Sequential Dynamic Curve Warning System.* Final Report. FHWA-15-CAI-012. Iowa State University. November 2015.

[2] Albin et al. *Low-Cost Treatments for Horizontal Curve Safety 2016*. Final Report. FHWA-SA-15-084. Pennsylvania Transportation Institute. January 2016.

Role of Asset Management Systems

Components of dynamic curve warning systems and the data produced by these systems could be utilized with asset management systems, such as MnDOT's Transportation Asset Management System (TAMS). For example, components (i.e. field devices and related systems) may be entered into an asset management system to track installation dates, maintenance schedules, repairs conducted, and other information to assist agencies in managing assets. In some cases, data from dynamic curve warning field devices (e.g. speed detection) may be communicated to asset management systems for long-term storage and access by administrators, technicians, or other stakeholders. Data communications to asset management systems are typically managed through optional components of a dynamic curve warning system (e.g. via the ATMS), and as such are secondary to local dynamic curve warning systems. Any specific functions of asset management systems related to dynamic curve warning will be addressed during final design of the dynamic curve warning systems, as applicable.

Examples of Communications Technologies Supporting Dynamic Curve Warning

The dynamic curve warning application relies upon a number of communications technologies (detailed in a separate document - *Model System Engineering Document, ITS Application: Communications*) to transfer the dynamic curve warning information from field devices to eventual end users. The following table summarizes examples of communications technologies used today.

Table 3: Example of Current Communications Supporting Dynamic Curve Warning

Dynamic Curve Warning Application Communications	Communications Technologies Supporting Dynamic Curve Warning Applications
Speed detection to warning signs	• **Short-range wireline or wireless communications** – Ethernet or serial connections using fiber or copper mediums or WiFi, microwave, or FM radio, depending on local conditions, to support communications over short distances between the speed detection and warning signs.
Dynamic curve warning field systems to ATMS	• **Long-range communications** – Ethernet connections using fiber or copper mediums to communicate speed detection information from the dynamic curve warning field systems to the ATMS. • **DOT operated Local Area Network (LAN) or Wide Area Network (WAN)** – Private communications network that allows a connection between the dynamic curve warning field systems and the ATMS with standard security concerns. • **Commercial wireless communications** – Services provided by third party providers over commercial networks, such as cellular, allow wireless communications of speed detection information from the dynamic curve warning field systems to the ATMS. • **Virtual Private Network (VPN) over public internet** – Secure and encrypted communications over less secure networks and the public internet allow communication of speed detection data from the dynamic curve warning field systems to the ATMS in locations where agency owned communications are not practical.

Dynamic Curve Warning Application Communications	Communications Technologies Supporting Dynamic Curve Warning Applications
ATMS to CAVs (dynamic curve warnings)	• **Public internet** – Use of the public internet allows information (e.g. dynamic curve warning information) to be shared with CAVs. • **Commercial wireless communications** – Services provided by third party providers over commercial networks, such as cellular, allow wireless communications of dynamic curve warning information from the ATMS to CAVs.

Stakeholders and Needs

Stakeholders

Table 4 identifies the stakeholder groups that interface with one or more aspects of dynamic curve warning system deployment and operations.

Table 4: Dynamic Curve Warning Stakeholders/Users

Stakeholder	Description
Travelers	Vehicle drivers operating traditional vehicles and CAVs.
Operators	Operators responsible for performing freeway or arterial operations and entry of road conditions and alerts. Where a communications connection to the ATMS is warranted and available, operators may view historical logs of system activations, or test the operational status of dynamic curve warning system components using electrical current sensing devices, as available.
Traffic Engineers	Engineers that assist with planning and designing dynamic curve warning systems. This may include determining the need for a system deployment and setting design parameters. Design parameters may include the pre-determined speed at which the curve warning sign is activated (curve threshold speed), the duration of display of the warning once activated, and placement of advanced warning sign(s) in relation to the start of the curve, to allow adequate distance for drivers to reduce speeds after viewing the sign(s) and before reaching the curve.
Administrators	A combination of operators and technical staff responsible for configuring the ATMS to interact with dynamic curve warning systems.
Technicians and Installers	Technical staff responsible for installing, maintaining, and troubleshooting dynamic curve warning system field equipment based on the approved designs and equipment installation instructions.
CAV Infrastructure Systems and CAVs	External systems that include both CAV infrastructure systems (systems operated by MnDOT) and CAVs (vehicles and on-board units in the vehicles) that support connected and automated vehicle operations. CAVs may receive dynamic curve warning notices and alert drivers. CAVs may also be a source for geometric roadway statuses that are detected by sensors on vehicles.

Stakeholder Needs

Table 5 identifies a series of problems or challenges and the related needs for each stakeholder identified above. Note that some needs are listed as optional needs (e.g. “may need…” or “when a connection to the ATMS is present…”) depending on various situations, such as whether the local dynamic curve warning system has a connection to the ATMS.

Table 5: Challenges/Needs

Problem/Challenge	Needs (As a Result of the Problem/Challenge)
Travelers Needs	
- Travelers en-route to their destination may be traveling at high speeds when approaching curves and may increase the likelihood of roadway departures or rollovers.	***Need 1: Real-time, En-route, Local Dynamic Curve Warning Notification*** Travelers need visual alerts that their speed is exceeding curve threshold speeds identified by the agency, with enough time to adjust their speed accordingly prior to reaching the curve.
Operators Needs	
- Vehicles may approach horizontal curves at speeds that create an unsafe condition at any time.	***Need 2: Automated Activation of Local Dynamic Curve Warning Displays*** In locations where dynamic curve warning systems are deployed, operators need the vehicle speed to be detected and local warning signs to be activated or de-activated, without requiring operator involvement. Operators may need additional detection when truck rollover is considered.
Traffic Engineers Needs	
- Dynamic curve warning systems are intended to alert vehicles traveling too fast, but if the systems display too often, they may lose effectiveness at alerting travelers.	***Need 3: Design of Dynamic Curve Warning Parameters*** Traffic engineers need a configurable dynamic curve warning system such that they can determine the curve threshold speed for when the warning system activates at each location. Traffic engineers may need additional options for configurations (e.g. vehicle weight, height, length) when truck rollover is considered.
Administrators Needs	
- It is important to identify issues with devices as early as possible, to implement repairs or replacements and minimize disruption in dynamic curve warning system operations.	***Need 4: Dynamic Curve Warning System Assessment*** Administrators need the ability to query and understand the operational status of dynamic curve warning system field devices. Depending on whether dynamic curve warning system field equipment has a connection to the ATMS, this assessment may occur in the field or remotely.
- Dynamic curve warning systems may require periodic configuration to adjust parameters such as the curve threshold speed.	***Need 5: Local Dynamic Curve Warning System Configuration*** When a connection to the ATMS is deployed, administrators need to be able to configure the local dynamic curve warning systems remotely through the ATMS. The curve threshold speed will be configurable and part of the design at each location. Administrators may need additional configurable options (e.g. lowering or raising height threshold, length threshold, or weight threshold) when truck rollover is considered for a location.

Problem/Challenge	Needs (As a Result of the Problem/Challenge)
- It is important to understand whether drivers reduce their speeds in response to dynamic curve warning displays, in order to understand effectiveness of curve warning systems.	***Need 6: Traffic Data to Assess Driver Response to Dynamic Curve Warning Displays*** When a connection to the ATMS is deployed, administrators need speed data from optional speed detection, to assess vehicle speeds upstream and downstream of the curve warning sign in order to determine the effectiveness of the curve warning systems.
- Administrators could benefit from historical data, to understand the timing and extent of overall system operations.	***Need 7: Access to Historical Data from Dynamic Curve Warning Systems*** When a connection to the ATMS is deployed, operators need a mechanism to access historical data from dynamic curve warning systems, such as reports of system activations and data from speed detection, to help them understand the frequency of activations and impacts to the road segment when recurring instances of dynamic curve warning activations occur.
Technicians and Installers Needs	
- Proper use of field equipment to detect and disseminate dynamic curve warnings require communications, power, and installation at the deployment sites.	***Need 8: Field Device Supporting infrastructure*** Technicians and installers need power, communications, and support structures to be available at locations where field equipment for dynamic curve warning systems is deployed. Note: power may be locally generated (e.g. solar, wind); local communications may not be able to provide a connection to the ATMS. Battery backup may also be considered, based on local decisions.
- Equipment deployed in the field must not harm technicians, installers, or anyone in vicinity of the equipment.	***Need 9: Safety Standards*** Technicians and installers need the field devices to adhere to appropriate safety standards, specifications, and protocols.
- Devices that are not compatible with existing equipment or systems may not be able to be installed or could require significant staff effort during installation.	***Need 10: Equipment Consistency*** Technicians and installers need consistency and compatibility in the dynamic curve warning equipment to achieve efficiencies in procurement, maintenance, and training.
CAV Infrastructure Systems and CAVs Needs	
- CAVs will benefit from data from nearby vehicles.	***Need 11: Vehicle to Vehicle Data Exchange*** CAVs need real-time, low latency data from other CAVs to exchange data that could describe curve warning locations.
- CAVs will benefit from curve warning alerts and notices provided by DOT-owned infrastructure, as additional automated driving systems and capabilities are integrated into vehicles.	***Need 12: Vehicle Use of Infrastructure-generated Curve Warnings*** CAVs need to receive infrastructure-generated data describing curve advisory speeds and curve threshold speeds for alerts.

Operational Concepts

The operational concepts below are presented for dynamic curve warning systems that may or may not have a communications connection to the ATMS. The provision of a communications connection to the ATMS is expected to be a local design decision based on factors that would determine whether local conditions warrant additional monitoring on the dynamic curve warning system. These factors include the location of the roadway within the larger transportation network, potential impact to travelers, and availability and cost to provide communications.

Travelers' Perspective

Table 6 describes the dynamic curve warning operational concepts from the travelers' perspective, and relates each concept to a need, as defined in the previous section.

Table 6: Dynamic Curve Warning Operational Concepts – Travelers' Perspective

Need (Travelers' Perspective)	Operational Concept
Travelers' Perspective related to ***Need 1: Real-Time, En-route, Local Dynamic Curve Warning Notification***	1.1 Travelers driving on selected routes that are unaware that they are approaching a horizontal curve may observe static signs, blinking chevrons, blank-out signs, and/or DMS alerting them to a curve ahead. 1.2 Travelers will view warning signs in advance of the horizontal curve, with enough time to reduce their speed prior to entering the curve. 1.3 At times when it is detected that a vehicle speed exceeds the designated curve threshold speed, the flashing beacons will be activated on static signs, chevrons will blink, blank outs signs will display a message, or a DMS message will be displayed, and travelers will be alerted as they approach the horizonal curve. 1.4 Upon seeing the activated warning sign, it is anticipated that travelers will slow down and proceed with caution as they approach the horizontal curve.

Operators' Perspective

Table 7 describes the dynamic curve warning operational concepts from the operators' perspective, and relates each concept to a need, as defined in the previous section.

Table 7: Dynamic Curve Warning Operational Concepts – Operators' Perspective

Need (Operators' Perspective)	Operational Concept
Operators' perspectives related to: ***Need 2: Automated Activation of Local Dynamic Curve Warning Displays***	2.1 In locations where there is a history of more than typical crashes on a horizonal curve, there may be local dynamic curve warning system installed to automatically detect the speed of approaching vehicles and activate local displays based on whether the vehicle speed is higher than the curve threshold speed.

Need (Operators' Perspective)	Operational Concept
	2.2 The vehicle speed detection will be an automatic function and not require operator monitoring or input. 2.3 The activation of local displays for the travelers upstream of the location (e.g. static signs with flashing beacons, chevrons that blink, blank out signs, or DMS message) will not require operator input. 2.4 The activation displays will turn off automatically, without operator input at pre-determined time following the vehicle's detection in advance of the curve. The time that the display stops will be configurable and part of the design of each location.

Traffic Engineers' Perspective

Table 8 describes the dynamic curve warning operational concepts from the traffic engineers' perspective, and relates each concept to a need, as defined in the previous section.

Table 8: Dynamic Curve Warning Operational Concepts – Traffic Engineers' Perspective

Need (Operators' Perspective)	Operational Concept
Traffic Engineers' perspectives related to: ***Need 3: Design of Dynamic Curve Warning Parameters***	3.1 Traffic Engineers will develop the physical design in compliance with the Minnesota MUTCD (e.g. signs, size of beacon, etc) and other applicable standards and engineering practices for the dynamic curve warning system at each location that is configurable including: • Curve threshold speed and related algorithm for activation of sign; • Determination of whether additional detection (e.g. height, length, weight) is included in the algorithm for sign activation at the selected location; • Determination of the location of warning sign(s) and location of vehicle detection. • Determine the duration of activation (i.e. time until the system deactivates) depending upon factors such as: local speed limit, placement of sign, local sight distances. 3.2 Traffic Engineers may authorize configuration adjustments to dynamic curve warning systems (e.g. adjusting curve warning threshold speeds or placement of signs) based on data collection and analysis.

Administrators' Perspective

Table 9 describes the dynamic curve warning operational concepts from the administrators' perspective, and relates each concept to a need, as defined in the previous section.

Table 9: Dynamic Curve Warning Operational Concepts - Administrators' Perspective

Need (Administrators' Perspective)	Operational Concept
Administrators' perspective related to ***Need 4: Dynamic Curve Warning System Assessment***	4.1 Administrators will query and understand the operational status of dynamic curve warning system field devices, using tools such as electrical current sensing devices, as available. 4.2 If a communications connection to the ATMS is present, administrators may use the ATMS to connect to electrical current sensing devices remotely, to test the operability of dynamic curve warning system field devices. 4.3 If a communications connection to the ATMS is present, the ATMS may include functionality to identify faulty sensors at the site of the dynamic curve warning system. When the ATMS generates message identifying the faulty sensor within the ATMS, administrators will initiate maintenance activities to repair or replace the faulty sensor.
Administrators' perspective related to ***Need 5: Local Dynamic Curve Warning System Configuration***	5.1 Administrators will configure the local dynamic curve warning systems once they are installed, if a communications connection to the ATMS is present. Configuration will link the local dynamic curve warning system to the ATMS to establish its location in order to process alerts received and assign them properly to roads in the ATMS. 5.2 In situations where a communications connection to the ATMS is present and either the dynamic curve warning system is modified or upgraded or the ATMS is upgraded, configuration may be required to maintain compatibility. 5.3 Administrators may perform portions of the dynamic curve warning system configuration in the field or remotely when a communications connection to the ATMS is present. 5.4 Administrators may connect the local dynamic curve warning system to related systems and devices such as a nearby video field devices, when these components are present in the deployment.
Administrators' perspective related to ***Need 6: Traffic Data to Assess Driver Response to Dynamic Curve Warning Displays***	6.1 When optional speed detection data is available via a communications connection to the ATMS, administrators will access vehicle speed data from the ATMS to assess driver response to dynamic curve warning displays. 6.2 Administrators will utilize optional speed detection data from locations upstream and downstream of the warning signs, along with system activation timestamps, to determine whether vehicles adjust their speeds in response to warning sign activations, in order to help determine effectiveness of the dynamic curve warning system. Data

Need (Administrators' Perspective)	Operational Concept
	collected and analyzed may include vehicle classification and truck/high profile vehicle detections.
Operators' perspectives related to ***Need 7: Access to Historical Data from Dynamic Curve Warning Systems***	7.1 Administrators will view historical data from speed detection and past instances of dynamic curve warning system activations and de-activations, to help debrief from incidents or to understand the frequency and timing of the conditions when vehicle speeds exceeds the curve advisory speed or curve threshold speed.

Technicians/Installers' Perspective

Table 10 describes the dynamic curve warning operational concepts from the perspective of the technicians and installers of dynamic curve warning system field devices, and relates each concept to a need, as defined in the previous section.

Table 10: Dynamic Curve Warning Operational Concepts - Technicians/Installers' Perspective

Need (Technicians/Installers' Perspective)	Operational Concept
Technicians and Installers' Perspectives related to ***Need 8: Field Device Supporting Infrastructure***	8.1 Dynamic curve warning system field devices will be deployed at locations where that they are accessible to communications and power, which may be locally generated by solar or wind. 8.2 Dynamic curve warning system field devices will be deployed such that communications and power will not be negatively impacted by any anticipated adverse conditions such as flooding or snow build-up. 8.3 Dynamic curve warning system field devices will be deployed such that technicians and installers can access the devices to perform maintenance. 8.4 Dynamic curve warning system field devices will be mounted on appropriate support structures, as needed. 8.5 Speed detectors will be calibrated to activate dynamic curve warning systems when vehicle speeds exceed the curve threshold speed.
Technicians and Installers' Perspectives related to ***Need 9: Safety Standards***	9.1 Technicians and installers need the dynamic curve warning system field devices to adhere to appropriate safety standards, specifications, and protocols. Equipment deployed in the field must not harm technicians, installers, or anyone in vicinity of the equipment. 9.2 Technicians and installers will be responsible for performing appropriate temporary traffic control (TTC) in compliance

Need (Technicians/Installers' Perspective)	Operational Concept
	with the Minnesota MUTCD when installing or performing field work on dynamic curve warning systems.
Technicians and Installers' Perspectives related to ***Need 10: Equipment Consistency***	10.1 Legacy field devices for dynamic curve warning systems will continue to be used. 10.2 Procurement of new field devices for dynamic curve warning systems will be consistent with in-place devices to the extent possible, so that installers and technicians will be well-trained to install and repair new devices and can interchange parts. 10.3 New field devices for dynamic curve warning systems will be compatible with existing equipment and systems such as communications (fiber, etc.) and data management systems (e.g. IRIS), even if there are no current plans for a communications connection to the ATMS. 10.4 Consistency and compatibility needs will not prevent or inhibit the testing and eventual production use of new products or services. MnDOT will continue to benefit from advances in technology. 10.5 Selection of new equipment or software tools will be done in a way that ensures interoperability and consistency with latest standards and technologies. 10.6 Testing to determine if RSUs are broadcasting advisory speed messages appropriately will be done with hand-held or vehicle-based detection devices.

CAV Infrastructure Systems and CAVs' Perspective

Table 11 describes the dynamic curve warning operational concepts from the perspective of CAV infrastructure systems and CAVs, and relates each concept to a need, as defined in the previous section.

Table 11: Dynamic curve Warning Operational Concepts - CAV Infrastructure Systems and CAVs' Perspective

Need (CAV Infrastructure Systems and CAVs)	Operational Concept
CAV Infrastructure Systems and CAVs' Perspectives related to ***Need 11: Vehicle to Vehicle Data Exchange***	11.1 CAVs (including agency owned CAVs) are expected to broadcast BSM continuously as they drive the Minnesota roadways. BSMs might be used by other CAVs or by MnDOT systems to understand the speed of vehicles in the curves. 11.2 Vehicles may also be equipped to broadcast supplemental messages (either continuously or through Event Driven Configurable Messaging (EDCM) communications) that could identify when situations such as hard braking or strong steering occur. These data could be used by agencies to identify locations where vehicles are not slowing to safe

	speeds and to support consideration of additional signing or warning systems. 11.3 Agency or privately owned CAVs may receive and process these supplemental messages from other vehicles and use this information to support on-board applications.
CAV Infrastructure Systems and CAVs' Perspectives related to ***Need 13: Vehicle Use of Infrastructure-generated Curve Warnings***	12.1 MnDOT may connect RSUs to the curve warning system's field devices to broadcast messages describing advisory speeds for the curve. 12.2 The RSU broadcast will require creation of standardized messages (typically the road safety message RSM) and supporting location references and security credentials. This message assembly may be performed by the dynamic curve warning system or the RSU, depending on local design. 12.3 MnDOT technicians may use hand-held or vehicle-based detection devices to receive messages broadcast by RSUs and determine if the RSUs are broadcasting advisory speed messages appropriately.

Operational Scenarios/Roles and Responsibilities

Roles and Responsibilities

During planning and design of dynamic curve warning systems, it is important for deploying agencies to determine agency-level roles for ownership, operation, and maintenance of dynamic curve warning systems, which will be carried out after such systems are deployed. Specifically, during planning and design, agencies will determine:

- ***System Ownership:*** Define the agency that will own the dynamic curve warning system after it is deployed;
- ***System Operation:*** Designate the agency (or unit within the agency) that will be responsible for operating the system on an ongoing basis; and
- ***System Maintenance:*** Designate the agency (or unit within the agency) that will be responsible for performing routine and long-term maintenance of the system, including preventative maintenance, any needed repairs, and replacement of failing or obsolete field equipment.

The table below provides a high-level summary of the roles and responsibilities of the stakeholder groups for dynamic curve warning systems.

Table 12: Operation and Maintenance Roles and Responsibilities

User Group	Role/Responsibility
Travelers	• View messages on dynamic curve warning signs to make decisions about reducing vehicle speeds in anticipation of a horizonal curve.
Operators	• Monitor activations of the dynamic curve warning systems if connected to the ATMS. • View nearby cameras (if available) to assess warning sign display statuses.
Traffic Engineers	• Determine design details including warning sign types, sign placement, curve threshold speeds, and messages that will be displayed to travelers.
Administrators	• Configure new dynamic curve warning systems to the ATMS (if connected to the ATMS). • Query the operational status of dynamic curve warning system equipment using the ATMS, to identify operational issues. • Receive automatic notifications about operational issues (if connected to the ATMS). • Notify technicians and installers of operational issues, to initiate repairs as needed. • Access vehicle speed data and dynamic curve warning system activation history (if connected to the ATMS) to evaluate the effectiveness of dynamic curve warning systems.
Technicians/Installers	• Prepare needed designs for dynamic curve warning system supporting infrastructure and support structures. • Install dynamic curve warning systems (including needed traffic control).

User Group	Role/Responsibility
	• Troubleshoot technical issues with the dynamic curve warning systems in the field and ATMS software (if connected to ATMS) and make repairs. • Perform routine maintenance in accordance with MnDOT ITS field device guidance. • Participate in configuring dynamic curve warning systems with the ATMS (if connected to ATMS).

Operational Scenarios

Scenarios are intended to describe examples of how users would interact with the dynamic curve warning systems in various situations and specifically to provide a temporal description of the sequence of events. The following scenarios briefly describe how users would be impacted and how they are expected to respond.

- Scenario A: Deploying a Dynamic Curve Warning System
- Scenario B: Dynamic Curve Warning System Monitoring Connected to ATMS
- Scenario C: Maintenance and Repair of Dynamic Curve Warning Systems
- Scenario D: Deploying a Dynamic Curve Warning System Connected to Vehicle Classification Detection
- Scenario E: CAV Use of Messages from RSUs at Dynamic Curve Warning Systems

Scenario A: Deploying a Dynamic Curve Warning System

MnDOT District 4 staff identify a horizontal curve that has a history of more than typical crashes. District 4 staff determine after trying static warning signs and reviewing guidance provided by the Minnesota MUTCD and other applicable standards and engineering practices that the location would benefit from a dynamic curve warning system. The Traffic Engineer during the planning for the dynamic curve warning deployment identifies the warning sign type, sign placement, curve threshold speed, and messages that will be displayed to the travelers. District 4 then works with the Regional Transportation Management Center (RTMC) staff to determine it will be connected to ATMS. During deployment, installers work with administrators and operators to configure the dynamic curve warning system to the ATMS such that it can be recognized by operators using the ATMS. The dynamic curve warning system is not near a local power connection, so it is powered using a combination of battery and solar power.

Scenario B: Dynamic Curve Warning System Connected with ATMS

A dynamic curve warning system deployed in central Minnesota is connected to the ATMS. As a traveler's speed in advance of the dynamic curve warning system site exceeds the curve threshold speed, the speed detector detects the condition and triggers activation of the warning sign. The dynamic curve warning system is an automated function and does not require operator monitoring or input. However, because the dynamic curve warning system is connected to the ATMS, administrators may query the system activation in the ATMS to understand the number and timing of activations. Operators may view nearby cameras to view the operational status of the warning sign.

Scenario C: Maintenance and Repair of Dynamic Curve Warning Systems

Over the course of a few weeks during the winter months, MnDOT district field staff periodically drive by a dynamic curve warning system and notice that it is consistently not activating when vehicle speeds appear to exceed the curve advisory speed. The district field staff contact administrators and technicians to inform them that the dynamic curve warning system may not be operating properly. A technician travels to the site to trouble-shoot the issue. The technician determines that one of the speed detectors is not working properly and replaces the faulty device. Several miles away in the same district, a dynamic curve warning system is connected to the ATMS. At this site, one of the sensors is not operating properly. The ATMS includes functionality (i.e. algorithms) to assess the operability of the sensors on a regular basis to identify faulty sensors. When this sensor at the site fails, the ATMS recognizes the failure and generates a message in the ATMS indicating the location of the faulty sensor. Upon viewing the message in the ATMS, operators contact administrators and technicians to inform them of the faulty sensor. Technicians replace the faulty sensor at the site of the dynamic curve warning system and operations are not impacted.

Scenario D: Deploying a Dynamic Curve Warning System Connected to Vehicle Classification Detection

A dynamic curve warning system deployed in southern Minnesota includes speed detection as well as vehicle classification sensors. As a vehicle approaches the dynamic curve warning system, the vehicle's speed is measured, and one or more detection devices identify the vehicle classification. The curve warning system's processing includes an algorithm that considers the data available and determines vehicles most susceptible to rollover or a roadway departure at the curve. In this example, the combination of the vehicle speed and vehicle classification trigger the activation of the warning sign. The dynamic curve warning system is an automated function and does not require operator monitoring or input. The vehicle views the alert from the dynamic curve warning sign and slows down. The dynamic curve warning sign automatically shuts off once the vehicle passes with no operator input.

Scenario E: CAV Use of Messages from RSUs at Dynamic Curve Warning Systems

MnDOT is operating a dynamic curve warning system with a roadside unit (RSU) that broadcasts messages describing the advisory curve's threshold speed. A nearby vehicle equipped with CAV technology is approaching the curve traveling at a speed that exceeds the curve threshold speed. The CAV is operating an on-board unit (OBU) application that receives and processes the curve advisory speed messages from the RSU and provides the curve advisory speed to the driver inside the vehicle with additional alert indicators specific to the vehicle type, at which time the driver decreases their vehicle's speed prior to reaching the curve.

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 dynamic curve warning 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.

The core system requirements in Table 13, below, are necessary for a dynamic curve warning system to perform local system activations and de-activations at the site of the deployment. For various optional components to integrate with the dynamic curve warning system, some requirements will have dependencies and are noted with a "dependency" designation following the requirement. As such, some requirements would need to be met by other systems (separate from the dynamic curve warning system) in order to perform the functions as described. In particular, deployments where the dynamic curve warning system is connected to an ATMS, requirements noted as "ATMS dependency" indicate requirements that the ATMS would need to meet in order for the system to be fully integrated with the dynamic curve warning system and perform the functions described.

Table 13: Dynamic Curve Warning System Requirements by Need

Need	System Requirement
Travelers	
1. Travelers need visual alerts that their speed is exceeding curve threshold speeds identified by the agency, with enough time to adjust their speed accordingly prior to reaching the curve.	1.1. In locations of horizontal curves that have a history of more than typical crashes, dynamic curve warning system deployments shall be considered, to advise travelers in advance of the horizontal curve. 1.2. Dynamic curve warning systems shall activate visual alerts to drivers in advance of the horizontal curve when the curve threshold speed is exceeded. 1.3. Warning signs for dynamic curve warning systems shall be located such that the sign displays are visible to approaching drivers. 1.4. Warning signs (types, placements, etc.) shall be designed in accordance with the Minnesota MUTCD. 1.5. Warning signs shall be placed in advance of the horizontal curve, at a distance such that the signs provide adequate perception-response time for the driver. (See Minnesota MUTCD, Section 2C, to view Guidance for Advance Placement of Warning Signs.)

Need	System Requirement
Operators	
2. In locations where dynamic curve warning systems are deployed, operators need the vehicle speed to be detected and local warning signs to be activated or de-activated, without requiring operator involvement. Operators may need additional detection when truck rollover is considered.	2.1. The detection of vehicle speed exceeding the curve threshold speed shall automatically activate the warning sign displays to alert travelers in advance of the horizontal curve. 2.2. The dynamic curve warning activations shall turn off automatically at a predetermined time after the dynamic warning sign is activated. 2.3. To the extent practical, dynamic curve warning system components (i.e. field devices) shall be compliant with National Transportation Communications for ITS Protocol (NTCIP) standards.
Traffic Engineers	
3. Traffic engineers need a configurable dynamic curve warning system such that they can determine the curve threshold speed for when the warning system activates at each location. Traffic engineers may need additional options for configurations (e.g. vehicle weight, height, length) when truck rollover is considered.	3.1. The dynamic curve warning system shall be capable of adjusting the curve threshold speed locally in the field. 3.2. When communications connection to the ATMS is present the ATMS shall provide a mechanism for operators to adjust the curve threshold speed remotely and update the parameters at the curve warning system. (ATMS dependency)
Administrators	
4. Administrators need the ability to query and understand the operational status of dynamic curve warning system field devices. Depending on whether dynamic curve warning system field equipment has a connection to the ATMS, this assessment may occur in the field or remotely.	4.1. When a communications connection to the ATMS is present and electrical current sensing devices are available, these devices shall be capable of being polled through the ATMS, to remotely query the operational status of field devices. 4.2. When a communications connection to the ATMS is present and electrical current sensing devices are available, the dynamic curve warning system shall provide automatic notifications to the ATMS, regarding operational issues with field devices. 4.3. When a communications connection to the ATMS is present, the ATMS may be capable of identifying faulty sensors at the site of the dynamic curve warning system and generating a

Need	System Requirement
	message in the ATMS that shows the location of the faulty sensor. (ATMS dependency)
5. When a connection to the ATMS is deployed, administrators need to be able to configure the local dynamic curve warning systems remotely through the ATMS. The curve threshold speed will be configurable and part of the design at each location. Administrators may need additional configurable options (e.g. lowering or raising height threshold, length threshold, or weight threshold) when truck rollover is considered for a location.	5.1. When a communications connection to the ATMS is present, the ATMS shall allow users to add and delete dynamic curve warning systems in the ATMS once they are installed. (ATMS dependency) 5.2. When a communications connection to the ATMS is present, the ATMS shall allow users to establish the dynamic curve warning system location in the ATMS. (ATMS dependency) 5.3. When a communications connection to the ATMS is present, the dynamic curve warning system shall support local on-site configuration of the field devices to the ATMS.
6. When a connection to the ATMS is deployed, administrators need speed data from optional speed detection, to assess vehicle speeds upstream and downstream of the curve warning sign in order to determine the effectiveness of the curve warning systems.	6.1. When a connection to the ATMS is present, the ATMS shall allow users to access data from the dynamic curve warning system (such as speed data, vehicle classifications, and truck/high provide data), with corresponding timestamps of system activations and de-activations. (ATMS dependency) 6.2. When a connection to the ATMS is present, the ATMS shall allow users to query and access dynamic curve warning system data and corresponding detection data and create customized reports suitable for data analysis. (ATMS dependency)
7. When a connection to the ATMS is deployed, operators need a mechanism to access historical data from dynamic curve warning systems, such as reports of system activations and data from speed detection, to help them understand the frequency of activations and impacts to the road segment when recurring instances of	7.1. When a connection to the ATMS is present, the ATMS may have a mechanism for users to view and create reports of past dynamic curve warning system activations and de-activations, including corresponding timestamps. (ATMS dependency) 7.2. When a connection to the ATMS is present, the ATMS may have a mechanism for users to view and create reports showing detection data from dynamic curve warning system systems with corresponding timestamps. (ATMS dependency)

Need	System Requirement
dynamic curve warning activations occur.	
Technicians and Installers	
8. Technicians and installers need power, communications, and support structures to be available at locations where field equipment for dynamic curve warning systems is deployed. Note: power may be locally generated (e.g. solar, wind); local communications may not be able to provide a connection to the ATMS. Battery backup may also be considered, based on local decisions.	8.1. Dynamic curve warning system field devices shall be designed and installed in accordance with requirements for roadway clearance and crashworthiness (e.g. breakaway structures or protection.) 8.2. Dynamic curve warning system design shall include the approach to mounting the field devices. 8.3. Dynamic curve warning system design shall include power connections. 8.4. Dynamic curve warning system design shall include components to support local communications. 8.5. When a communications connection to the ATMS is present, the dynamic curve warning system design shall include components to support remote, long-distance communications. 8.6. Dynamic curve warning system design shall include adequate visibility of warning signs. 8.7. Dynamic curve warning system design shall include accessibility to field devices for maintenance and repairs.
9. Technicians and installers need the field devices to adhere to appropriate safety standards, specifications, and protocols.	9.1. A professional engineer registered in the State of Minnesota shall review and approve all design details of the complete dynamic curve warning system field deployment. The detection mechanisms, communications, traveler displays, and CAV dissemination components should all be considered in the design. 9.2. Dynamic curve warning system field devices shall include components to support safe lifting, transport, and installation of the devices. 9.3. Dynamic curve warning system field devices shall meet current specifications as approved by MnDOT or the agency/owner that is deploying and operating the dynamic curve warning system. 9.4. Dynamic curve warning system design shall include TTC plans for installing or performing field work on dynamic curve warning system field devices.

Need	System Requirement
10. Technicians and installers need consistency and compatibility in the dynamic curve warning equipment to achieve efficiencies in procurement, maintenance, and training.	10.1. Dynamic curve warning system field devices shall be compatible with existing equipment and systems such as communications (e.g. fiber, etc.) and related systems and devices (e.g. ATMS, etc.) 10.2. Newly procured dynamic curve warning system field devices shall be consistent with similar in-place devices to the extent possible, as technicians and installers are well-trained to install and repair these devices and can interchange parts. 10.3. Dynamic curve warning system field devices shall utilize MnDOT standardized components, as available. 10.4. Dynamic curve warning system field devices, equipment, and software shall be procured to ensure interoperability and consistency with the latest standards and technologies. 10.5. Consistency and compatibility needs shall not prevent or inhibit testing or eventual production use of new products or services.
CAV Infrastructure Systems and CAVs	
11. CAVs need real-time, low latency data from other CAVs to exchange data that could describe curve warning locations.	11.1. Agency or privately owned CAVs may receive and process BSMs from other vehicles and use this information to support such applications as curve warning. 11.2. Agency or privately owned CAVs may receive and process BSM Part 2 messages (such as traction control status and antilock brake system status) from other vehicles and use this information to support such applications as curve warning.
12. CAVs need to receive infrastructure-generated data describing curve advisory speeds and curve threshold speeds for alerts.	12.1. DOTs may locate roadside units to broadcast information such as the curve advisory speed and/or the curve threshold speed for the immediately downstream curve that will be received by CAVs. 12.2. When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall generate standards compliant messages (e.g. Road Safety Message (RSM) or other message formats used by the agency) for broadcast by the RSU. 12.3. When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall assign security credentials to the messages according to the agency approach and requirements for secure connections. 12.4. When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall attach either low-fidelity or high-fidelity location reference (MAP) messages to accompany the warnings that are broadcast.

Need	System Requirement
	12.5. DOTs may use network cellular communications to broadcast messages describing dynamic curve warning messages. 12.6. CAVs may ingest the messages describing dynamic curve conditions from the roadside units or cellular communications, to support on-board applications or automated driving system features.

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 dynamic curve warning;
- Concepts for the use of dynamic curve warning; 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 14 below identifies the needs/potential solutions included in the Minnesota ITS Architecture that are addressed through concepts for the use of dynamic curve warning systems 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 dynamic curve warning system stakeholder need(s) that were influenced or derived based on each service package.

Table 14: Summary of Local and National ITS and CAV Architecture References Mapped to Dynamic Curve Warning Needs

MN Statewide Regional ITS Architecture: Need/Potential Solutions	ARC-IT: Service Packages	ARC-IT: Processes	Dynamic Curve Warning Stakeholder Needs Influenced by each Service Package
• ATMS32 – Provide curve speed warnings • ATMS18 – Provide dynamic speed feedback to drivers and enforcement agencies	• VS05 Curve Speed Warning	• Provide Driver with Personal Travel Information	• Need 1: Real-time, En-route, Local Dynamic Curve Warning Notification • Need 3: Design of Dynamic Curve Warning Parameters
• ATMS32 – Provide curve speed warnings • ATMS18 – Provide dynamic speed feedback to drivers and enforcement agencies	• TM12 Dynamic Roadway Warning	• Process Traffic Sensor Data	• Need 2: Automated Activation of Local Dynamic Curve Warning Displays
• ATMS32 – Provide curve speed warnings • ATMS18 – Provide dynamic speed feedback to drivers and enforcement agencies	• TM12 Dynamic Roadway Warning	• Collect Vehicle Speed	• Need 2: Automated Activation of Local Dynamic Curve Warning Displays
• None identified at this time	• TI07 In-Vehicle Signage	• Output in-vehicle Signage Data	• Need 12: Vehicle Use of Infrastructure-generated Curve Warnings • Need 3: Design of Dynamic Curve Warning Parameters
• ATMS42 - Use roadside data collectors to determine locations with frequent occurrence of speeding	• TM12 Dynamic Roadway Warning	• Retrieve Traffic Data	• Need 7: Access to Historical Data from Dynamic Curve Warning Systems

MN Statewide Regional ITS Architecture: Need/Potential Solutions	ARC-IT: Service Packages	ARC-IT: Processes	Dynamic Curve Warning Stakeholder Needs Influenced by each Service Package
• ATMS42 - Use roadside data collectors to determine locations with frequent occurrence of speeding	• TM12 Dynamic Roadway Warning	• Process Traffic Data for Storage	• Need 7: Access to Historical Data from Dynamic Curve Warning Systems
• ATMS32 – Provide curve speed warnings	• TM12 Dynamic Roadway Warning	• Retrieve Traffic Data	• Need 6: Traffic Data to Assess Driver Response to Dynamic Curve Warning Displays • Need 7: Access to Historical Data from Dynamic Curve Warning Systems
• ATMS32 – Provide curve speed warnings	• TM12 Dynamic Roadway Warning	• Process Traffic Data for Storage	• Need 6: Traffic Data to Assess Driver Response to Dynamic Curve Warning Displays • Need 7: Access to Historical Data from Dynamic Curve Warning Systems
• ATMS32 – Provide curve speed warnings	• TM12 Dynamic Roadway Warning	• Provide Traffic Operations Personnel Traffic Data Interface	• Need 4: Dynamic Curve Warning System Assessment
• ATMS32 – Provide curve speed warnings	• TM12 Dynamic Roadway Warning	• Manage Roadway Warning System	• Need 5: Local Dynamic Curve Warning System Configuration

Model Test Plan

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

Each dynamic curve warning 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 dynamic curve warning 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 dynamic curve warning) 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 dynamic curve warning. 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 dynamic curve warning to verify the quality assurance/quality control and dynamic curve warning 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 in the field to test the actual deployment and functionality of the dynamic curve warning.

Table 15: Model Test Plan for Dynamic Curve Warning

System Requirement		Testing Instructions	Type of Result	Comments / Notes
1.1	In locations of horizontal curves that have a history of more than typical crashes, dynamic curve warning system deployments shall be considered, to advise travelers in advance of the horizontal curve.	Advisory requirement – no testing required	N/A	
1.2	Dynamic curve warning systems shall activate visual alerts to drivers in advance of the horizontal curve when the curve threshold speed is exceeded.	Field – Conduct tests to confirm all supporting infrastructure is installed and operational (e.g. detection, power, communications) so the dynamic curve warning system activates the visual alerts when an approaching vehicle exceeds the curve threshold speed.	Pass/Fail	
1.3	Warning signs for dynamic curve warning systems shall be located such that the sign displays are visible to approaching drivers.	Field – Conduct tests to confirm that warning signs and any associated visual indicators (e.g. flashing beacons, blank out signs) are visible and legible to drivers at posted speeds.	Pass/Fail	
1.4	Warning signs (types, placements, etc.) shall be designed in accordance with the Minnesota MUTCD.	Design – Confirm that the warning signs comply with the Minnesota MUTCD. Field – Confirm that the installed warning signs are consistent with the approved design.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	
1.5	Warning signs shall be placed in advance of the horizontal curve, at a distance such that the signs provide adequate perception-response time for the driver. (See Minnesota MUTCD, Section 2C, to view Guidance for Advance Placement of Warning Signs.)	Design – Confirm that the warning sign placements in the design plans are appropriate per Minnesota MUTCD guidance and engineering judgement. Field – Confirm that the placement of installed warning signs is consistent with the approved design. Confirm that warning signs are placed	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	

System Requirement		Testing Instructions	Type of Result	Comments / Notes
		such that field conditions (roadway geometry, sight obstructions) do not impact the drivers' ability to view the signs and reduce vehicle speeds accordingly.		
2.1	The detection of vehicle speed exceeding the curve threshold speed shall automatically activate the warning sign displays to alert travelers in advance of the horizontal curve.	Design – Confirm that the dynamic curve warning system display is designed to automatically activate when a vehicle exceeding the curve threshold is detected at the designed distance in advance of the curve. Field – Conduct test to confirm that the dynamic curve warning system will activate when the system detects an approaching vehicle exceeding the curve threshold speed is detected at the designed distance in advance of the curve.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	
2.2	The dynamic curve warning activations shall turn off automatically at a predetermined time after the dynamic warning sign is activated.	Design – Confirm that the dynamic curve warning system display is designed to automatically de-activate after the pre-determined time after activation has elapsed. Field – Conduct test to confirm that the dynamic curve warning system display de-activates when the pre-determined time after activation has elapsed.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	
2.3	To the extent practical, dynamic curve warning system components (i.e. field devices) shall be compliant with National Transportation Communications for ITS Protocol (NTCIP) standards.	Design – Confirm NTCIP compliance for the dynamic curve warning system's field devices, to the extent practical.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
3.1	The dynamic curve warning system shall be capable of adjusting the curve threshold speed locally in the field.	Design – Confirm that the dynamic curve warning system is configurable to adjust the curve threshold speed at the field device components. Field – Conduct tests to adjust the curve threshold speeds at the field devices, confirming that the appropriate device(s) are configurable to trigger the warning mechanism at the configured curve threshold speed.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	
3.2	When communications connection to the ATMS is present the ATMS shall provide a mechanism for operators to adjust the curve threshold speed remotely and update the parameters at the curve warning system. (ATMS dependency)	Design – Confirm that the dynamic curve warning system is configurable to adjust the curve threshold speed (and other parameters as deployed) at the field device components. Field – Conduct tests to adjust the curve threshold speeds at the field devices, confirming that the appropriate device(s) are configurable to trigger the warning mechanism at the configured curve threshold speed (and other parameters as deployed.)	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field – Pass/Fail	ATMS dependency
4.1	When a communications connection to the ATMS is present and electrical current sensing devices are available, these devices shall be capable of being polled through the ATMS, to remotely query the operational status of field devices.	Design – Confirm that the design includes current sensing devices that the ATMS can poll to check the operational status of the field equipment. Field – Confirm that the field equipment can be polled using the ATMS to check the operational status of field equipment using current sensing devices.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	
4.2	When a communications connection to the ATMS is present and electrical	Design – Confirm that the design includes current sensing devices that automatically	Design – Pass/Fail per Content Review. If	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
	current sensing devices are available, the dynamic curve warning system shall provide automatic notifications to the ATMS, regarding operational issues with field devices.	notify the ATMS of operational issues with field equipment. Field – View the ATMS to confirm that automatic notifications are received by the ATMS (from the dynamic curve warning system warning system) when operational issues with the field equipment occur.	"Fail," indicate changes required. Field - Pass/Fail	
4.3	If a communications connection to the ATMS is present, the ATMS may be capable of identifying faulty sensors at the site of the dynamic curve warning system and generating a message in the ATMS that shows the location of the faulty sensor. (ATMS dependency)	Field – Conduct a test with an absent or faulty sensor to ensure that the ATMS detects that the sensor is not functioning properly.	Field – Pass/Fail	ATMS dependency
5.1	When a communications connection to the ATMS is present, the ATMS shall allow users to add and delete dynamic curve warning systems in the ATMS once they are installed. (ATMS dependency)	Design – Confirm that the design allows the dynamic curve warning system to be added or deleted in the ATMS. Field – Confirm that operators can use the ATMS user interface to add or delete the dynamic curve warning system.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	ATMS dependency
5.2	When a communications connection to the ATMS is present, the ATMS shall allow users to establish the dynamic curve warning system location in the ATMS. (ATMS dependency)	Design – Confirm that the design allows the curve warning system location to be established in the ATMS. Field – Confirm that the ATMS has established the dynamic curve warning system location in the ATMS.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	ATMS dependency

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
5.3	When a communications connection to the ATMS is present, the dynamic curve warning system shall support local on-site configuration of the field devices to the ATMS.	Design – Confirm that the design allows the dynamic curve warning system to be configured to the ATMS from on-site at the field devices. Field – Confirm that field staff can configure the dynamic curve warning system to the ATMS at the site of the field devices.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	
6.1	When a connection to the ATMS is present, the ATMS shall allow users to access data from the dynamic curve warning system (such as speed data, vehicle classifications, and truck/high profile data), with corresponding timestamps of system activations and de-activations. (ATMS dependency)	Design – Confirm that the design allows for detection data from the dynamic curve warning to be accessed, along with corresponding system activation and de-activation timestamps. Field – Confirm that ATMS users can view and access detection dta from vehicles approaching the dynamic curve warning, with corresponding timestamps of system activations and de-activations.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	ATMS dependency
6.2	When a connection to the ATMS is present, the ATMS shall allow users to query and access dynamic curve warning system data and corresponding detection data and create customized reports suitable for data analysis. (ATMS dependency)	Design – Confirm that the design allows the ATMS to create customized reports showing dynamic curve warning system data (e.g. activations and de-activations) and speed data approaching the curve. Field – Confirm that ATMS users can create customized reports showing data from dynamic curve warning systems and speed data of vehicles approaching the curve.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	ATMS dependency
7.1	When a connection to the ATMS is present, the ATMS may have a mechanism for users to view and create	Design – Confirm that the design allows the ATMS to view and create reports of dynamic	Design – Pass/Fail per Content Review. If	ATMS dependency

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
	reports of past dynamic curve warning system activations and de-activations, including corresponding timestamps. (ATMS dependency)	curve warning activations and de-activations with corresponding timestamps. Field – Confirm that ATMS users can view and create reports of dynamic curve warning system activations and de-activations with corresponding timestamps.	"Fail," indicate changes required. Field - Pass/Fail	
7.2	When a connection to the ATMS is present, the ATMS may have a mechanism for users to view and create reports showing detection data, with corresponding timestamps. (ATMS dependency)	Design – Confirm that the design allows the ATMS to view and create reports of data from the curve warning system's detectors. Field – Confirm that ATMS users can view and create reports of data from the curve warning system's detectors.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	ATMS dependency
8.1	Dynamic curve warning system field devices shall be designed and installed in accordance with requirements for roadway clearance and crashworthiness (e.g. breakaway structures or protection.)	Design – Confirm that the dynamic curve warning system design meets current requirements for roadway clearance and crashworthiness. FAT – Confirm that dynamic curve warning system equipment meets current requirements for crashworthiness. Field – Confirm that field equipment is installed per design in accordance roadway clearance and crashworthiness requirements per the approved design.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. FAT – Pass/Fail Field - Pass/Fail	
8.2	Dynamic curve warning system design shall include the approach to mounting the field devices.	Design – Confirm installation considerations are included in design.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
8.3	Dynamic curve warning system design shall include power connections.	Design – Confirm presence of power connections for external sources or self-sustaining power units.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
8.4	Dynamic curve warning system design shall include components to support local communications.	Design – Confirm presence of components for local communications.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
8.5	When a communications connection to the ATMS is present, the dynamic curve warning system design shall include components to support remote, long-distance communications.	Design – Confirm presence of components for remote communications.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
8.6	Dynamic curve warning system design shall include adequate visibility of warning signs.	Design – Confirm that the warning sign design allows for adequate visibility to drivers.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
8.7	Dynamic curve warning system design shall include accessibility to field devices for maintenance and repairs.	Design – Confirm that the design locates field devices in an accessible location for field staff to perform maintenance. Field – Confirm that the field devices can be accessed by field staff for maintenance activities.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	
9.1	A professional engineer registered in the State of Minnesota shall review and approve all design details of the	Design – Confirm review and approval by a Minnesota professional engineer.	Design – Pass/Fail per Content Review. If	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
	complete dynamic curve warning system field deployment. The detection mechanisms, communications, traveler displays, and CAV dissemination components should all be considered in the design.		"Fail," indicate changes required.	
9.2	Dynamic curve warning system field devices shall include components to support safe lifting, transport, and installation of the devices.	FAT – Confirm presence of components to support safe movement and installation.	FAT – Pass/Fail	
9.3	Dynamic curve warning system field devices shall meet current specifications as approved by MnDOT or the agency/owner that is deploying and operating the dynamic curve warning system.	Design – Confirm that specifications have been developed or acquired from the agency/owner and are approved for use in final acceptance. Design - Confirm that specifications of the deploying/operating agency/owner are met. FAT – Confirm that field devices meet the agency/owner specifications.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. FAT – Pass/Fail	
9.4	Dynamic curve warning system design shall include TTC plans for installing or performing field work on dynamic curve warning system field devices.	Design – Confirm that the design includes TTC plans.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
10.1	Dynamic curve warning system field devices shall be compatible with existing equipment and systems such as communications (e.g. fiber, etc.) and related systems and devices (e.g. ATMS, etc.)	Design – Confirm that the design is compatible with existing equipment and systems for communications and data management, per local design choice. Field – Confirm that the field devices can communicate and interface with communications and related systems.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. Field - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
10.2	Newly procured dynamic curve warning system field devices shall be consistent with similar in-place devices to the extent possible, as technicians and installers are well-trained to install and repair these devices and can interchange parts.	Advisory requirement – no testing required.	N/A	
10.3	Dynamic curve warning system field devices shall utilize MnDOT standardized components, as available.	Design – Confirm that the design contains MnDOT standardized components, as available.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required.	
10.4	Dynamic curve warning system field devices, equipment, and software shall be procured to ensure interoperability and consistency with the latest standards and technologies.	Design – Confirm that the design is compatible and interoperable with current standards. FAT – Confirm that equipment conforms with current standards.	Design – Pass/Fail per Content Review. If "Fail," indicate changes required. FAT - Pass/Fail	
10.5	Consistency and compatibility needs shall not prevent or inhibit testing or eventual production use of new products or services.	Advisory requirement – no testing required	N/A	
11.1	Agency or privately owned CAVs may receive and process BSMs from other vehicles and use this information to support such applications as curve warning.	Advisory requirement – no testing required	N/A	
11.2	Agency or privately owned CAVs may receive and process BSM Part 2 messages (such as traction control status and antilock brake system	Advisory requirement – no testing required	N/A	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
	status) from other vehicles and use this information to support such applications as curve warning.			
12.1	DOTs may locate roadside units to broadcast information such as the curve advisory speed and/or the curve threshold speed for the immediately downstream curve that will be received by CAVs.	Design – Confirm roadside unit communications and processing capabilities. FAT – Demonstration of roadside unit ability to: • Generate a CAV message in a standard format that conveys the curve warning related message. • Broadcast the generated CAV messages over industry standard communications, with appropriate message certifications. Field – Confirm with one or more on-board devices that the roadside unit is able to: • Generate a CAV message in a standard format that conveys the curve warning related message. • Broadcast the generated CAV message to via one or more standard communications mechanisms.	Design – Pass/Fail per Content Review. If “Fail,” indicate changes required. FAT - Pass/Fail Field – Pass/Fail	
12.2	When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall generate standards compliant messages (e.g. Road Safety Message (RSM) or other message formats used	Design – Confirm standards compliant messages generated by roadside units or dynamic curve warning systems.	Design – Pass/Fail per Content Review. If “Fail,” indicate changes required. FAT - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
	by the agency) for broadcast by the RSU.	FAT – Demonstration of roadside unit or dynamic curve warning system to generate standards compliant CAV messages. Field – Confirm with one or more on-board devices that the roadside unit or the dynamic curve warning system is able to generate standards compliant CAV messages.	Field – Pass/Fail	
12.3	When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall assign security credentials to the messages according to the agency approach and requirements for secure connections.	Design – Confirm that the security credentialing approach for CAV messages meets the agency approach and requirements for secure connections. FAT – Demonstration of roadside unit or dynamic curve warning system to assign security credentials to CAV messages. Field – Confirm with one or more on-board devices that CAV messages received from the roadside unit or the dynamic curve warning system have been assigned appropriate security credentials.	Design – Pass/Fail per Content Review. If “Fail,” indicate changes required. FAT - Pass/Fail Field – Pass/Fail	
12.4	When local RSUs are connected to dynamic curve warning systems, either the warning systems or the RSU shall attach either low-fidelity or high-fidelity location reference (MAP) messages to accompany the warnings that are broadcast.	Design – Confirm that the RSU or dynamic curve warning system design includes ability to attach low-fidelity or high-fidelity location reference (MAP) messages to the warning messages that are broadcast. FAT – Demonstration that the RSU or dynamic curve warning system provides CAV messages that contain appropriate MAP messages.	Design – Pass/Fail per Content Review. If “Fail,” indicate changes required. FAT - Pass/Fail	

	System Requirement	Testing Instructions	Type of Result	Comments / Notes
		Field – Confirm with one or more on-board devices that CAV messages received from the roadside unit or the dynamic curve warning system contain appropriate MAP messages.	Field – Pass/Fail	
12.5	DOTs may use network cellular communications to broadcast messages describing dynamic curve warning messages.	Advisory requirement – no testing required	N/A	
12.6	CAVs may ingest the messages describing dynamic curve conditions from the roadside units or cellular communications, to support on-board applications or automated driving system features.	Advisory requirement – no testing required	N/A	