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CONNECTED ROADWAY CLASSIFICATION SYSTEM DEVELOPMENT

FINAL REPORT

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ABSTRACT

The roadway infrastructure needed for safe and efficient operation of connected vehicles (CVs) and automated vehicles (AVs) is evolving as more knowledge is exchanged between the automotive industry and the infrastructure owner/operators (IOOs). A common language and reference about the infrastructure's role in automation would further facilitate the exchange of information. The National Cooperative Highway Research Program (NCHRP) 20-24(112) Connected Roadway Classification System (CRCS) Development project developed a framework that could be used to classify three approaches to enhancing the roadway infrastructure readiness: increasing connectivity (allowing vehicles to "talk to roadways"), enhancing roadway elements such as signing and pavement markings (allowing vehicles to "see the roadway"), and controlling the operational design domain (ODD) within which vehicles will operate ("simplifying the roadway").

A workshop was also held as part of NCHRP 24(112) in Detroit, Michigan, on June 4, 2018. The workshop was an invitation-only event attracting 52 participants from the public sector, private sector, non-profit associations, and academia that discussed what is needed in a CRCS to support a future connected and automated vehicle environment. The attendees recommended that the research project deliverables be kept simple, accommodate future advancement of technologies and vehicle/technology capabilities, and promote a standard terminology and approach across all states.

This report presents a CRCS framework for IOOs to assess three infrastructure approaches for four different classification levels. Specific criteria are presented for each classification level by infrastructure approach. The framework also identifies gaps in the CV and AV industry knowledge. The CRCS framework is flexible to allow an IOO to assess the framework in a way that is consistent with an agency's goals and objectives.

EXECUTIVE SUMMARY

The roadway infrastructure needed for safe and efficient operation of connected vehicles (CVs) and automated vehicles (AVs) is evolving as more knowledge is exchanged between the automotive industry and the infrastructure owner/operators (IOOs). A common language and reference system about the infrastructure's role in automation would further facilitate the exchange of information. The National Cooperative Highway Research Program (NCHRP) 20-24(112) Connected Roadway Classification System (CRCS) Development project developed a framework for use in assessing the infrastructure and incorporating new knowledge that emerges on how infrastructure can support CVs and AVs.

To develop this CRCS framework, a workshop was held as part of NCHRP 24(112) in Detroit, Michigan, on June 4, 2018, in conjunction with the 2018 Intelligent Transportation Society of America (ITS America) Annual Meeting. This workshop brought together representatives from the infrastructure and automotive industry to discuss a CRCS framework for existing and future connected and automated vehicle environments. Separate CRCS workshop proceedings that cover the pre-workshop white papers and presentations, workshop discussions, and workshop findings are being published by the Transportation Research Board (TRB).

The NCHRP 20-24(112) research team introduced three infrastructure approaches to classifying improvements made to roadways to support CVs and AVs. First, roadways can be improved to increase a vehicle's ability to connect to the infrastructure and other vehicles (termed "talking to the road"). Second, roadway infrastructure can be improved to support the safety and operation of AVs (termed "seeing the road"). Third, roadway infrastructure can be changed to create an operational design domain (ODD) that supports better vehicle safety automation and operation (termed "simplifying the road"). The workshop participants affirmed these infrastructure classification approaches as ways to support both connectivity and automation.

One recurring recommendation from workshop participants and the NCHPR panel members was to keep any future CRCS simple and implementable. Simplicity includes the classification levels and criteria for classification. If the CRCS is not simple, it will not be adopted and used by agencies across the country (and potentially internationally). Simplicity also reflects the level of effort to implement or use a CRCS. Many comments from the workshop participants centered on using the CRCS to guide planning, investment, and deployment. For a CRCS to be used by a wide variety of users, it must be straightforward and direct in application.

This report presents a CRCS framework for IOOs to assess the three infrastructure approaches of (1) taking to the road, (2) seeing the road, and (3) simplifying the road for four different classification levels. These classification levels are as follows: in need of upgrade and maintenance, meets current best practices, meets emerging markets (1–5 years), and meets next decade market (10 years). Specific criteria are presented for each classification level by infrastructure approach. The framework also identifies gaps in the CV and AV industry knowledge. The CRCS framework is flexible to allow an IOO to assess the framework in a way that is consistent with an agency's goals and objectives.

The research team recommends that the CRCS be updated and revisited approximately every 5 years. This recommendation recognizes that technology (both vehicle and infrastructure) and research findings evolve over time. The CRCS will be kept relevant with advances in CV and AV technology and current research with regular updates. The report highlights several professional organizations and partnerships that could aid in maintaining the CRCS. The support from these organizations and partnerships could also lead to adoption of the CRCS as part of recommended practice and eventually part of geometric design and uniform traffic control device guidance.

An overview of the CRCS framework is presented in Table 1. The criteria for each classification level are presented by the three different infrastructure approaches.

Table 1. CRCS Framework Overview

Infrastructure Approach	What It Is	CRCS Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1–5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	• Limited or no fiber installed • Limited or no cellular coverage • Limited or no roadside devices with communication • Signal equipment outdated with no connections • Temporary TCD deployed with no communication	• Fiber along roadway with access points • Good cellular coverage • Updated signal controller, meets MUTCD, connected as part of system • Infrastructure has no V2I capability • TCDs connected	• DSRC or C-V2X nodes tied into fiber • Signal is equipped with V2I communication capability • Infrastructure has V2I capability • TCDs able to connect to cellular or fiber	• Small cells deployed along roadway with 5G coverage • Signal transmits SPaT messages • Infrastructure transmits information on conditions with local processing capability
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	• Roadway assets are not in digital form • Signs and markings are either not present and/or fall short of MUTCD retroreflectivity guidance • Signals in need of upgrade	• Digital inventory of roadway assets exists • Signs and markings are present and meet MUTCD retroreflectivity guidance • Traffic signal equipment meets MUTCD	• Major corridors or areas have digital maps • Signs and markings meet revised MUTCD CAV visibility guidance • Signals are consistent, visible, and use glare reduction backplates	• Signs and markings include technology that provides for future machine visibility and processing • Research is needed on how AVs see signals
Simplifying	Design & operations for AV vehicles & their uses	• Infrastructure geometry, temporary TCDs, and permanent TCDs may not meet AASHTO or MUTCD guidelines • Pavement in poor condition	• Infrastructure geometry meets AASHTO design guidance • Pavement free of defects • Temporary and permanent TCDs meet MUTCD guidance	• Infrastructure geometry is designed to facilitate navigation by CVs/AVs • Navigational aids are V2I capable • Research is needed	• Infrastructure geometry and navigational aids are specifically designed for CVs/AVs only • Research is needed

CHAPTER 1. BACKGROUND

Departments of transportation (DOTs), metropolitan planning organizations (MPOs), and IOOs are seeking to make smart, timely investments to support the deployment of connected and automated vehicle (CAV) technologies operating on their transportation networks. Those investments must align with the agency's goals and objectives, such as safety, mobility, and agency efficiency. To be effective, however, the investments must also align with the CAV technologies being developed by the automotive industry, AV start-ups, and the aftermarket device community. IOOs are making infrastructure investments on construction horizons (1–5 years), design horizons (10–15 years), and planning horizons (25–35 years).

It is difficult to anticipate the exact technologies that will be on vehicle fleets in the future. What DOTs/MPOs/IOOs need, and what this project aimed to develop, was a framework to help align agency interests with other IOOs and with emerging CAV technologies. This framework will assist the entire transportation industry in identifying infrastructure improvements to support the safety and performance of CAVs operating on the transportation network. Having such a framework allows IOOs to plan and program infrastructure for CAVs within the context of their current planning, design, construction, maintenance, and operation activities.

IOOs are responsible for the transportation infrastructure and network. With the introduction of CVs and AVs, there is greater interest in how roadways should be planned, designed, operated, and maintained to optimize safety and mobility. Roadways today are designed for the driver's capabilities. Horizontal curves along highways are dependent on acceptable lateral acceleration for drivers. Vertical curves are dependent on safe stopping sight distance, which involves the driver's perception/reaction time to react to an obstacle in the road. Fonts and materials on roadway signs are based on driver visual acuity to read information. However, technologies and sensors on CVs and AVs have the potential to perceive the roadway environment in different ways to assist drivers in performing the driving task or perform the driving task themselves. To achieve safe and efficient vehicle operation, IOOs need guidance on what infrastructure is needed to support CVs and AVs operating on streets and highways.

One concept that has been suggested is to create a roadway classification system that would categorize the roadway infrastructure to support CAVs. The NCHRP 20-24(112) CRCS Development project was initiated to create a classification system that would allow IOOs and the automotive industry to have a common description of this infrastructure. The objective of this project was to develop consensus on a CRCS that will be useful to DOTs, MPOs, and IOOs that are planning or implementing CAV-compatible infrastructure. To accomplish this, the project team sought participation from vehicle original equipment manufacturers and other private-sector interests (e.g., other CAV developers, transportation network companies, digital map providers, and cellular telecommunications companies).

This report presents a recommended CRCS for IOOs to use to assess their roadway infrastructure for different infrastructure approaches. The CRCS provides a common framework for the infrastructure and for automotive industries to discuss what knowledge is needed to fill the gaps in relationships between the infrastructure and CAVs. This report also provides a synthesis of literature and information available to inform a CRCS, a summary of the CRCS workshop conducted under this project, a discussion of the development behind the CRCS framework, and an overview of additional research and efforts needed to maintain the CRCS going forward.

NEED FOR CLASSIFICATION SYSTEM

Roadway classification enables clear communication of roadway readiness for CVs and AVs. As these technologies emerge, a classification system provides the framework for discussion between the automotive and infrastructure industries. A classification system could also give drivers and passengers an understanding of their responsibilities on the roadways, removing the ambiguity that leads to inappropriate assignment of driving tasks. When is a human responsible for the driving task and when does the roadway support AV operation? Roadway infrastructure classification may also provide a means of externally verifying and enforcing vehicle compatibility with the comparable infrastructure of the roadway. Controls such as these can ultimately lead to safer roads. Infrastructure classification may contribute to defining roadways where CVs and AVs can safely navigate based on universal understanding of vehicle capabilities. Finally, redundancy between both vehicle and infrastructure is key to creating a safe and robust automated driving environment. As in the aerospace industry, redundant systems need to be in place to function when the primary system fails. The greater the degree of automation in vehicles, the greater the need for redundant systems to protect both vehicle and passengers from malfunctions. A roadway classification system could further provide roadway infrastructure descriptions of the appropriate degree of redundancy to ensure a safe and robust driving environment.

INFRASTRUCTURE AND ITS READINESS

The selection of a roadway classification system has tremendous implications to IOOs. For a jurisdiction to be ready and to help enable the full range of CV and AV benefits, infrastructure investments will need to be made in advance of widespread consumer adoption of vehicle technologies. While implementing these infrastructure changes in advance of widespread use will enable testing in a real-world environment, this implementation still requires an up-front investment not always considered politically and financially tenable to state and local public agencies.

Installation of traffic signal interfaces and roadside equipment will likely be the responsibility of state and local DOTs. This equipment will be used to send information about the infrastructure to vehicles and/or receive messages broadcast from vehicles. The automotive industry and other private entities may be involved in the development of other aspects of CV and AV systems, particularly for vehicle-based safety applications and security management systems, respectively.

The communications technology between vehicles and infrastructure, whether it is based on 5.9 Ghz dedicated short-range communication (DSRC), cellular, or an entirely different wireless system, will need to be fast, reliable, secure, private, and interoperable. The IOO will bear some responsibility, although the level to which is unclear. A backhaul communications network will be necessary to provide communication between the message handler/processor and management centers, typically via fiber-optic cable. Satellite communications, used for the transmission of time and location data from Global Navigation Satellite System satellites, will also be used.

Messages transmitted via these communications channels share data between infrastructure and vehicles. To ensure consistent understanding, these communication channels need to be standardized in terms of the message types that can be used and the data frames and data elements of which the messages are comprised.

While traditional intelligent transportation systems (ITSs) have the potential to greatly benefit from the enhanced data collection enabled by CVs, these systems will likely need to be updated to be ready to do so. Updating ITSs could include infrastructure investments such as the installation of roadside units that can receive data from CVs. Policy updates may also be required (e.g., on data sharing due to the large involvement of private entities). Some ITS devices, such as pedestrian detection equipment, will continue to be used to collect data not available via other sources, so the data these devices provide will need to be able to be processed by roadside units and provided to CVs.

Redundant systems may be necessary to support vehicle-to-infrastructure (V2I) applications, particularly for those that enable safety-critical applications. Special provisions will also need to be made for temporary changes to traffic patterns, such as work zones and road closures, and ideally this information will be communicated both in advance (when known) and in real time.

Infrastructure investments that help prepare a jurisdiction for CVs and AVs will have an impact on the planning, design, construction, maintenance, and operations of a transportation network. In the short/medium-term, existing standards may need to be modified, especially those for existing roadway components such as road markings and signage, to make them compatible with both human drivers and AV systems. Standards and regulations should be uniform across jurisdictions and state lines, so CVs can operate seamlessly throughout the country. Additional infrastructure changes may prove to be necessary after CVs are widely adopted. An infrastructure and ITS readiness approach to a CRCS could classify the roadway infrastructure as to its CV and ITS deployment status. The greater deployment of infrastructure detectors and sensors, roadside equipment, telecommunication technologies, and data backhaul equipment could enable high levels of CV and AV operations.

CHAPTER 2. CV AND AV CLASSIFICATION SYNTHESIS

This chapter provides a synthesis of the material on roadway classification related to CVs and AVs. A literature review was conducted through the Transportation Research Information System. Some related articles were identified, but there were very few published articles on CRCSs because this topic is an emerging concept. Additional information was identified in presentations made available at professional association meetings and electronic articles.

AUTOMATED VEHICLES

SAE Levels of Automation

The Society of Automotive Engineers (SAE) has defined levels of automation in its J3016 standard, titled *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (*1*). This standard was most recently updated in June 2018. The U.S. Department of Transportation (USDOT) has also supported these vehicle automation levels that classify the AV operation to facilitate a clear and consistent use of terminology (*2*). The full SAE levels, which are now the standard in the United States and internationally where SAE regulations are observed, are as follows:

- Level 0, the human driver does everything.
- Level 1, an automated system on the vehicle can sometimes assist the human driver in conducting some parts of the driving task.
- Level 2, an automated system on the vehicle can conduct some parts of the driving task while the human continues to monitor the driving environment and performs the rest of the driving task.
- Level 3, an automated system can both conduct some parts of the driving task and monitor the driving environment in some instances, but the human driver must be ready to take back control when the automated system requests.
- Level 4, an automated system can conduct the driving task and monitor the driving environment, and the human need not take back control, but the automated system can operate only in certain environments and under certain conditions.
- Level 5, the automated system can perform all driving tasks, under all conditions in which a human driver could perform them.

These levels of automation do not require anything from the infrastructure. The levels of automation are generally descriptive of the amount of automation and the relationship of the driver versus the vehicle. One approach to a CRCS would be to mirror these vehicle automation levels with roadway classification levels—that is, describe the infrastructure at each level of vehicle automation that would optimize the safety and efficiency of the vehicles. On the surface, this would seem straightforward. However, are infrastructure elements any less important at different levels of automation? Or are the infrastructure elements equally important for any level of automation? Maybe the infrastructure elements are more important at lower levels of automation. If so, the question concerns the location of infrastructure deployments and the functional classification of roadways on which they are deployed.

USDOT Automated Vehicles 3.0

In October 2018, USDOT published *Preparing for the Future of Transportation—Automated Vehicles 3.0*. One of the guiding principles is that the USDOT foresees mixed-use roadways where AVs operate alongside manually driven vehicles and other road users and anticipates on-road testing to improve AV performance. While this document does not specifically mention a roadway classification system pertaining to AVs, it does support many concepts that are related to a CRCS. First, pavement markings, signs, and other traffic control devices are important to both manually driven vehicles and AVs. The Federal Highway Administration (FHWA) will pursue an update to the *Manual on Uniform Traffic Control Devices* (MUTCD) to include traffic control needs for AVs. Second, USDOT is involved in many connected vehicle-to-everything (C-V2X) projects that include communication devices installed at the roadside. USDOT encourages the development of this connectivity to the infrastructure because it will improve AV efficiency and safety. Third, states may want to assess their road readiness for AVs. This could include assessing pavement markings, signs, and pavement conditions to benefit both manually driven vehicles and AVs. Fourth, USDOT recognizes that data exchange between AVs and the roadway environment will benefit AVs in both static and dynamic environments, especially in areas with work zones, highway-rail crossings, and managed lanes. Finally, transportation agencies should examine the operational design domain and types of streets on which AVs can operate. This includes reviewing complete street policies when planning automation deployments to seek how complete streets can enhance the safety and efficiency of AVs (*2*).

GEOMETRIC DESIGN FUNCTIONAL CLASSIFICATION

The geometric design of roadways is based on classifying roads by their functions. This section discusses the current policy and recent research.

AASHTO Green Book

The American Association of State Highway and Transportation Officials (AASHTO) publishes the document *A Policy on Geometric Design of Highways and Streets* (commonly referred to as the Green Book). The policy states that classification of highways based on operational systems, functional classes, or geometric types is important for communication among transportation professionals, decision makers, and the public.

The Green Book discusses the roadway network as a system with a hierarchy of functions being served. There are trade-offs between access and mobility, with higher functional roadway classes serving mobility and lower roadway classes providing vehicle access from various lane uses. The functional classes are principal arterial, minor arterial, collector, and local. There are also context classifications for the environment: rural, rural town, suburban, urban, and urban core. The criteria within the different classifications address trip length, lane use density, population density, roadway spacing, traffic type, and traffic volume (*3*).

NCHRP 855

NCHRP Research Report 855, *An Expanded Functional Classification System for Highways and Streets,* developed guidance for an expanded functional classification system (Expanded FCS) that has been incorporated into the AASHTO Green Book. The Expanded FCS takes into consideration environmental context, road functions, and user needs. The five distinct context categories identified in the Expanded FCS are rural, rural town, suburban, urban, and urban core. The Expanded FCS presents a matrix of these context categories divided by the functional classifications of principal arterial, minor arterial, collector, and local roadway. The primary factors to consider within each category of the matrix are development density, land uses, and building setbacks. The Expanded FCS process is to identify the context and roadway type, identify modal users, identify potential user ranges, identify other overlays (e.g., transit and trucks), and develop design considerations and alternatives (*4*).

COLORADO DOT CRCS

One of the challenges facing IOOs is the level to which they intend to equip their roadways for the impending rollout of CVs and AVs. Recognizing this, the Colorado Department of Transportation (CDOT) proposed a road classification system with six levels that relate to the roadway's ability to support CVs and AVs:

- Level 1: Unpaved and/or non-striped roads designed to a minimum standard level of safety and mobility.
- Level 2: Paved roads designed to AASHTO's guidance and pavement marking standards and signing designed to meet MUTCD standards. There is no ITS equipment or infrastructure to collect CV data. Access to cellular data service may be available.
- Level 3: ITS equipment operated by a traffic operation center (TOC) and/or one-way electronic data share between DOT/vehicle/user and/or mixed-use lanes.
- Level 4: Roadway or specific lane(s) equipped with adaptive ITS equipment (i.e., smart signals hold for vehicles, highway lighting that turns on for vehicles), with TOC override only and/or two-way data share between DOT/vehicle/user and/or lanes designated for vehicle Levels 3 and 4 only.
- Level 5: (Advance guideway system) roadway or specific lane(s) designed for vehicle Level 4 only, with additional features that may include inductive charging, advance/enhanced data sharing, and more. Additionally, no roadside signs are needed because all roadway information is directed to vehicles' on-board systems.
- Level 6: All lanes on a roadway designed for only vehicle Level 4 systems—no signs, signals, striping needed.

Two key observations can be made from the Colorado CRCS. The first is to identify roadways that may be insufficient for some uses. Some local or rural roads may be purpose-built for specific uses and not suitable for all users. For example, unpaved roads rarely have pavement markings that may be needed by AVs. The second observation on the Colorado CRCS has to do with the amount of detail in the Level 4 classification. The Level 4 classification describes the CAV environment. How the infrastructure is adapted for CVs, AVs without connectivity, or AVs with connectivity can be different. More detail on how geometric design, signs, pavement markings, traffic signals, and telecommunications will be deployed to support CV and AV operations would be valuable to IOOs.

CAPABILITY MATURITY MODEL

The capability maturity model (CMM) is a structure that originated in the software development industry. Recently, efforts have been made to apply the CMM concept to transportation operations and connected vehicles.

Transportation System Management and Operation CMM

In 2013, FHWA initiated a project to develop a series of six capability maturity frameworks (CMFs) based on the AASHTO transportation systems management and operations (TSMO) CMM. The intent was for the CMFs to elaborate on and be consistent with the AASHTO TSMO CMM but provide more focused assessment and suggest actions in each of the following operational program areas: traffic management, traffic incident management, planned special events, work zone management, road weather management, and traffic signal control.

The concept of a CMM for transportation operations emerged from Strategic Highway Research Program 2 (SHRP2) reliability projects L01 and L06, which promoted a process-driven approach to improve TSMO. The projects focused on the role of institutions and the business processes necessary to improve management of programs and projects. The FHWA CMM for TSMO attempts to develop a CMF for traffic management are directly linked to the CMM approach. By taking this approach, potential benefits can be realized by state DOTs, local agencies, and stakeholder partners in their TSMO programs. The purpose of the framework, available online, is to build consensus among stakeholders on institutional changes at an agency or regional level. The framework is used before any traffic management activities and strategies are implemented. It is not strategy specific; rather, the framework is specific to process areas that are applicable to traffic management concerns (*5*).

Connected Vehicle CMM

Gettman et al. looked at a CMM framework for developing a CV program. The effort was focused on helping public agencies prepare for creating a CV environment. The dimensions of the CMM were business processes, system and technology, performance measurement, organization, staffing, culture, and collaboration. The classification levels were as follows: Level 1—Exploration, Level 2—Initiated, Level 3—Integrated, and Level 4—Mainstreamed. The CV CMM provides a framework for IOOs to develop action plans for the implementation of CV program capabilities. A wide range of agency activities in each dimension are identified to provide the framework for development of a CV program plan. The CV CMM does address field devices and back-office procedures that would be deployed as part of the system and technology dimension, but it does not address the specific roadway elements that might support a CRCS (*6*).

INTERNATIONAL EFFORTS—INFRAMIX PROJECT

There have been some international efforts related to development of a CRCS, mostly in Europe. The European Union funded the INFRAMIX project through its Horizon 2020 research and innovation program in 2017. The objective of the INFRAMIX project is to prepare the roadway infrastructure with specific cost-effective modifications to support and accommodate the introduction of AVs. One effort within the project is to develop an infrastructure classification scheme to support AVs (*7*).

Carreras et al., in a paper presented at the 2018 ITS World Congress, presented a five-level infrastructure scheme on how infrastructure could support automated driving. The levels were identified as follows:

- Level A—Cooperative driving.
- Level B—Cooperative perception.
- Level C—Dynamic digital information.
- Level D—Static digital information/map support.
- Level E—Conventional infrastructure/no AV support.

The lowest level is Level E, in which AVs need to recognize the roadway geometry, pavement markings, and signs without any digital data being shared. Levels A through D imply some level of connectivity with the digital information being shared. Level D requires only sporadic connectivity to update map data and road rule information. Level C includes both static and dynamic data providing digital information to AVs, such as speed limits. Level B is where the infrastructure can monitor real-time conditions and share these data with AVs. Level A also includes real-time data from the infrastructure on conditions, but these data are being provided cooperatively so that the infrastructure is able to guide a group of or individual AVs to optimize the overall traffic flow (*8*).

Manganiaris, in a presentation to the ASECAP conference, presented the same classification scheme but further defined digital infrastructure, physical infrastructure, and operational infrastructure needed within each level. Digital infrastructure for Levels A, B, C, and D suggests the use of HD maps using cloud-based digital input for accurate sign positions. Levels A, B, and C include dynamic update of lane topography, and Levels A and B include the location of emergency zone stops. Physical infrastructure for Levels A and B includes elements to ensure continuous connectivity to enable V2X communication along segments using technology such as roadside units (RSUs). Level A also includes high-precision meteorological stations and in-pavement sensors to detect moisture, temperature, and strain. Level C uses dense location referencing points, while Level D includes variable message signs. Level E physical infrastructure includes vehicle-recognizable road traffic signs, color, and position; signs with speed limits, road curvature, and inclination; good lane markings on both sides; lane width based on standards; working zone signalization; and video cameras for real-time vehicle detection. The operational infrastructure for the five levels varies. Level A suggests dynamic guidance for individual and group vehicles that includes speed, gap, and lane advice and uses detailed weather information. Level B suggests microscopic traffic situations and data exchange with cloud services. Level C calls for automated updates of digital infrastructure and data processing. Level D suggests handling information related to warnings, incidents, and weather (*9*).

OTHER RELATED ARTICLES

The Wisconsin DOT Traffic Operations Infrastructure Plan (TOIP) outlines two goals. The first is to develop ITS solutions by corridors, and the second is to develop a prioritized list by corridors of the ITS solutions from the first goal. The analysis includes individual roadway segments having the same relative traffic volume, roadway capacity, and adjacent land use. The roadway types used to assess the technology recommendations include urban interstate, urban expressway, urban other, rural interstate, rural expressway, and rural other. These are essentially the higher functional roadway classifications outlined in the AASHTO Green Book.

A deployment density class (DDC) recommendation is given for every considered length of roadway. This DDC recommendation is designated as baseline, low, medium, or high to create a uniform standard for operations technology recommendations throughout the state in an easily communicable and understandable format. Criteria used are data values focusing on mobility, safety, and environmental conditions. Tiers group roadways by the level of operational technology deployment (baseline, low, medium, high). Thresholds are used to group values for a given roadway into a tier. The criteria are scored and then prioritized using a weighted factor. The DDC is matched to the tiers and is used to identify the package of operational solutions for the respective roadway segment. The key operational infrastructure for the developed corridors addresses surveillance and traffic flow management, traveler information, and signal systems. The TOIP was developed to provide a quantitative approach and tool that analyzes the operational needs of the Wisconsin highway system and to provide a structured approach to operations/ITS recommendations across the state. The statewide operations/ITS program allows planners and programmers to understand not only the capital program cost implications, but the ongoing maintenance, operations, and replacements commitments as well (*10*).

Tang and Beckon investigated a vision-based classification of differing road environments. The study looked at how machine vision systems used for AVs classify the road. They researched two classification methods to evaluate for near real-time classification of the road environment. The four-class method used four general roadway environments consisting of off-road, urban, major/trunk road, and multilane motorway/carriageway. The two-class method had a simplified roadway classification consisting of off-road and on-road. Researchers used a combined color and texture feature vector extracted from multiple subregions of a forward-facing on-vehicle camera view. The specifically constructed test video sequences of concatenated 10-s video segments corresponded to the different classes. For the two-class determination, an artificial neural network (ANN) classifier resulted in ~90–97 percent successful classification. However, the more complex four-class determination results showed ~80–85 percent. According to Tang and Beckon, “Prior analysis using a k-nearest neighbor (k-NN) classifier implies the inherent feature overlap within the current feature space and the resulting difficulty of the classification problem itself—not in the least due to ground truth ambiguity for any given frame outside of the temporal context of the sequence” (*11*).

Zhu et al. also examined how LIDAR-based sensor systems recognize intersections. They proposed a method for the use of a real-time 3D-point cloud-based intersection and road segment detection algorithm for AVs. The method is based on the analysis of the features from a dense 64-beam scanning LIDAR mounted on a vehicle’s rooftop. The proposed approach recognizes intersections in front of the AV and distinguishes between +-shaped and T-shaped intersections.

Researchers followed three steps: (1) build a grid map from point cloud data and remove the vehicle from the map; (2) launch a beam model and the launch point within an adaptive distance in front of the AV; and (3) exploit a trained classifier based on a support vector machine. The current road shape is then classified as an intersection and road segment and then recognized as a T-shaped intersection or +-shaped intersection (*12*).

A report for the Royal Automobile Club (RAC) Foundation focused on the infrastructure considerations for CVs and AVs from a policy, planning, and implementation perspective. The report highlighted that decisions about the infrastructure needs to start with the type of vehicles proposed for the respective roadway—whether the focus is truck platooning, shared mobility, or private vehicles. The road infrastructure asset classes include structures, roads, communications, drainage, and geotechnical features. The two approaches discussed for CAV implementation included CAVs being physically separated from other traffic and other road users (or physical separation in some areas but not in others); and CAVs retaining non-CAV capability so the driver can take over in mixed traffic or urban areas. For successful implementation, both strategies need to account for the condition, maintenance, renewal, and configuration of road infrastructure and the associated capital investment, operating costs, risks to other road users, and time delays.

The RAC Foundation report suggested that policymakers consider choosing CAV strategies that will relate to the road infrastructure needs that support each choice. The two issues that arise include whether the vehicle will be in charge, with either no role for a human driver or the driver only taking over control in limited circumstances, or the human driver will be in charge, with automation there to aid performance in the event of emergency or in degraded situations (*13*).

Lawson discussed the relationship between roadway infrastructure and safety for conventional vehicles and AVs. He suggested a star rating for specific road segments used by AVs. This rating is based on the qualities of the infrastructure, such as well-defined line markings. For example, "A road with excellent all-weather line marking may reduce the run-off risk to almost zero because there would be few foreseeable conditions under which an AV would not be kept on the road. The high-quality line marking coupled with the lane keeping attributes of the vehicle may mean that it would contribute to a 4-star rating for an AV. That same road may only rate 2-star for a conventional vehicle." Signalized intersections may have an advantage over roundabouts for AVs because they have more defined turning maneuvers and more predictable elements of stop-start traffic conditions at the intersection. Other examples for reducing traffic incidents with AVs are broken into six categories with accompanying suggested infrastructure needs:

- AV versus conventional vehicle—signing and marking; median barriers. Need to determine which type of intersections will be best for AVs.
- AV versus AV—signing and marking; connectivity with roadside infrastructure and with vehicles.
- AV versus infrastructure—signing and marking; connectivity.
- AV versus motorcycle—signing and marking; median barriers; motorcycle recognition by other vehicles and infrastructure.

- AV versus bicycle—signing and marking; median barriers; nearside segregation; priority treatments; bicycle recognition by others.
- AV versus pedestrian—pedestrian recognition by others; nearside segregation; crossing designs; priority treatments (*14*).

CHAPTER 3. FINDINGS AND APPLICATIONS

This chapter highlights the findings from the CRCS workshop and the CRCS development effort. The recommended criteria for and application of the CRCS are presented herein.

MONITORING THE DRIVING ENVIRONMENT

The promise of self-driving vehicles has been highlighted in the press, announced through official news releases by automobile manufacturers, and widely discussed in terms of related potential impacts on the economy, mobility, the environment, and societal interactions. With the collaborating influences of electric engines and mobility-as-a-service, there are high expectations for trailblazing innovations.

But we are not there yet. There is still a gap between today and that future when a machine relieves us of the driving responsibility and improves the safety of our transportation system. That gap between current conditions and future expectations begins to close as (a) the technology for vehicle automation improves, and (b) the existing human-driver designed roadway advances so that collectively they build that future.

From an automotive perspective, the path to full automation is centered on two tracks, as defined in the document *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, published as SAE J3016_201609, aka the SAE levels of driving automation (*1*). One path is **executing the driving task**, including steering, acceleration, and deceleration. As automation increases, the vehicle assumes more of those control tasks. The other path is **monitoring the driving environment**. As automation advances, the vehicle assumes more of the monitoring task and the human driver assumes less monitoring. Of the five levels of AVs, the last three, Levels 3–5, rely on the automated driving system to monitor the driving environment. The last two levels are where the driver has little to no need to monitor the environment. This second path, monitoring the driving environment, is where roadway infrastructure can play a critical role in closing the gap between expectations and results.

Human-Built Road

Since 1908 when the invention of the Model T first made cars widely available to the public, relationships with the roadway have been evident. As an example, there has been a steady interaction among the driver, technology on a vehicle (such as headlights), and buildout of the roadway. The industry advanced vehicle headlights from kerosene, to acetylene gas headlamps, to carbon-base lighting, to sealed beam headlamps, to halogens, to light-emitting diodes (LEDs). At the same time, roadway markings changed in color, location, purpose, material, and visibility. These changes were based on one's ability to monitor the roadway system—the human driver.

Seeing the Road

The past has been filled with changes; the future will be no different. The roadway monitoring task is moving from the human driver to the automated vehicle. Video cameras on vehicles will be taking the place of human eyes. Future vehicle optical sensors are moving beyond human capabilities to new technologies such as infrared sensors for night vision, as introduced in the Cadillac DeVille in 2000 and later migrated to the CT6 in 2015. Today, such technologies are being used for pedestrian and/or animal detection by a number of manufacturers including Honda, BMW, and Audi. Companies are also exploring the capability to add new content to the roadside visual environment. 3M is working on a connected road initiative that includes the concept of embedding a bar code equivalent in a road sign that is only visible with a sensor built for the infrared spectrum.

Infrastructure operators can work with the automotive industry and their vehicle sensors to improve recognition of the roadway; that is, they can improve the capability to "see the road."

Talking with the Road

Traffic signals have displayed the right of way to vehicles and pedestrians for over a hundred years. With today's technology and communications, the industry is prototyping and initiating deployments of traffic signals that broadcast their right-of-way status to vehicles that are listening with their own radios. AASHTO has authorized a program that encourages states to begin implementation of these broadcasts from traffic signals (called the Signal Phase and Timing [SPaT] Challenge).

Work zones are one of those unexpected infrastructure environments that cause AVs a challenge in navigating the driving environment. However, work zones are also getting smarter with increasing ability to communicate to other infrastructure elements and vehicles. Sensors are being placed in barricades and cones that monitor the traffic conditions and allow for real-time communication of work zone location, lane closure status, and traffic speeds.

Infrastructure operators can work with the automotive industry and their vehicle communications to receive information about roadway devices and conditions; that is, they can improve the capability to "talk with the road."

Simplifying the Road

Past practices of designing a safe roadway environment are changing as the vehicle fleet evolves to more connected, autonomous, and automated driving. Recognizing that impact, NCHRP is advancing research projects to assess the links between automation, roadway design, and safe traveling. In addition, the TRB Access Management Committee is discussing submission of a problem statement for consideration in the spring 2019 funding cycle for a topic called "Access Management Curbside Design for Autonomous Vehicles."

These three topics, automation, roadway design, and safe traveling, are key to building and operating a roadway infrastructure that supports the path of automation. Infrastructure operators can help close the gap between expectations and results by providing better conditions for vehicle monitoring of the environment.

Infrastructure Approaches

To frame the CRCS discussion, the research team identified four approaches that an IOO could take to prepare its infrastructure for CAVs. Figure 1 highlights these four approaches.

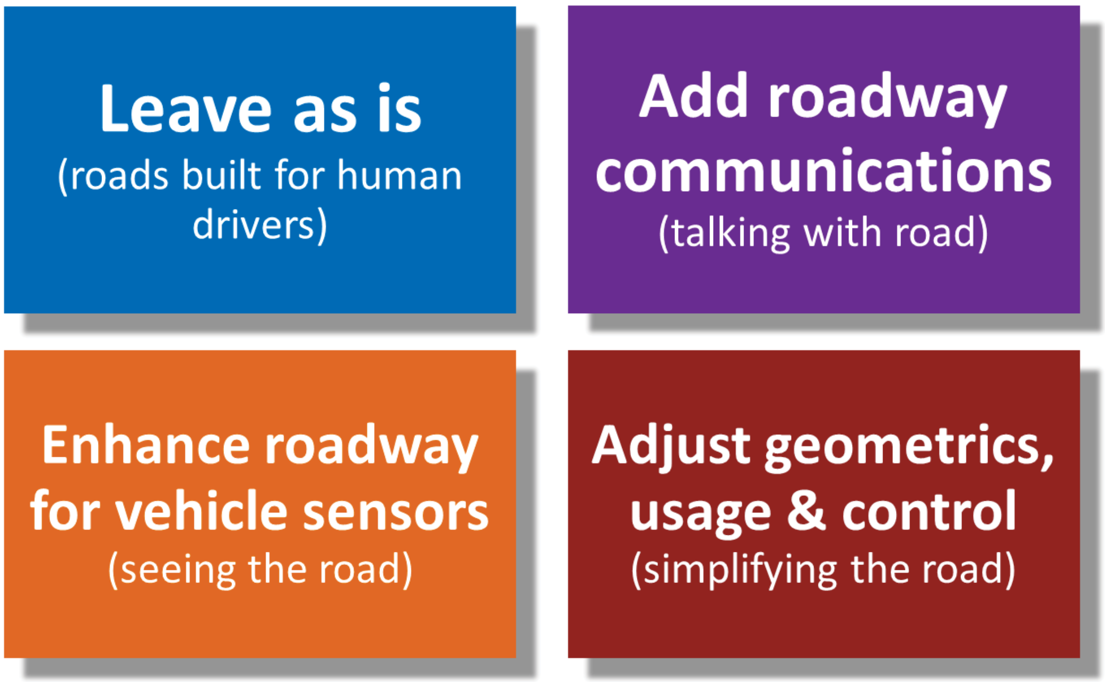

Figure 1. Different IOO Infrastructure Approaches

Leave As Is. The first approach is for an IOO to continue doing business as usual (upper-left box in Figure 1). An IOO continues to build roadway infrastructure for human-driven vehicles. The roadway infrastructure would still include technology for traditional ITS and transportation system management and operation. However, with limited budgets and uncertainty in technology development, the IOO would not make additional investment in infrastructure specifically for CAVs. The automotive companies, however, would continue to progress vehicle technology and automated driving features and deploy as they are today.

Add Roadway Communications. The second approach is to add communications technology along the roadway to allow for greater connectivity of CAVs (upper-right box in Figure 1). The approach is independent of the technology. Two current approaches are DSRC using the 5.9 GHz bandwidth and cellular communication, often identified as C-V2X. An IOO would deploy and construct communications systems that would allow for V2V and V2I. This approach is termed talking with the road.

Enhance Roadway for Vehicle Sensors. The third approach is to enhance the roadway infrastructure to improve safety and operation of AVs (lower-left box in Figure 1). Sensors on AVs, whether radar, machine vision, or LIDAR, are interpreting the driving environment. Improvements in the infrastructure can enhance the performance and accuracy of these sensors. Examples could be changes in the shape, size, or materials of signs, pavement markings, and traffic signal control systems. This approach is termed seeing the road.

Adjusting Geometrics, Usage, and Control. The fourth approach is to adjust the roadway geometric design to simplify the ODD for AVs to navigate the roadway (lower-right box in Figure 1). Simplifying the roadway could include changing usage or user access, changing the roadway control, or modifying the alignment or cross section to improve the AV safety and performance. For example, limiting the ODD to only controlled-access facilities such as interstate freeways is one form of changing the control. This approach is termed simplifying the road.

Systems View

With those infrastructure approaches defined, the research team prepared a system view of how those approaches could be used in an iterative manner to improve CAV capabilities and achieve greater benefits from these vehicle technologies. As shown in **Error! Reference source not found.**, AVs monitor the roadway as they drive through an ODD (this could be true for any driving automation system regardless of the level of automation). The IOOs can make investments in the roadway infrastructure and operations to improve the vehicle's ability to monitor the roadway. An IOO may improve the vehicle's ability to talk to the roadway, see the roadway, or navigate the roadway (by simplifying). These infrastructure improvements should result in enhancements in the AV capabilities. If the AV capabilities improve, then it is expected that the AV will achieve greater benefits.

There is a gap today between the ultimate benefits expected of CAVs and the actual benefits being realized. IOOs can help close the gap between expectations and results by providing infrastructure to assist the vehicle in monitoring the environment. The three infrastructure approaches that include the IOO making investments in the infrastructure are key to building and operating a roadway infrastructure that supports the path of automation.

Figure 2 ties these concepts together and illustrates them from a systems viewpoint. The figure tells the following story:

- Vehicle automation has great anticipated benefits.
- A gap exists between those ultimate benefits and today's AV performance.
- The SAE concept for progress of vehicle automation has two main paths: execution of the driving task and monitoring of the roadway environment.
- As automation increases, more of the roadway monitoring task is done by vehicle systems, not people. That path of monitoring the roadway environment gathers roadway knowledge that can be acted on by the automated driving task.
- IOOs continually make investments toward infrastructure and operations.
- Infrastructure operating organizations can contribute to roadway monitoring improvements that provide roadway knowledge. They can add communications for roadway devices (talking with the road). They can enhance the roadway environment for vehicle-based sensors (seeing the road). They can adjust geometrics, usage, and control of the roadway (simplifying the road).
- Those investments can improve the capabilities of AVs and decrease the gap between expectations and results.

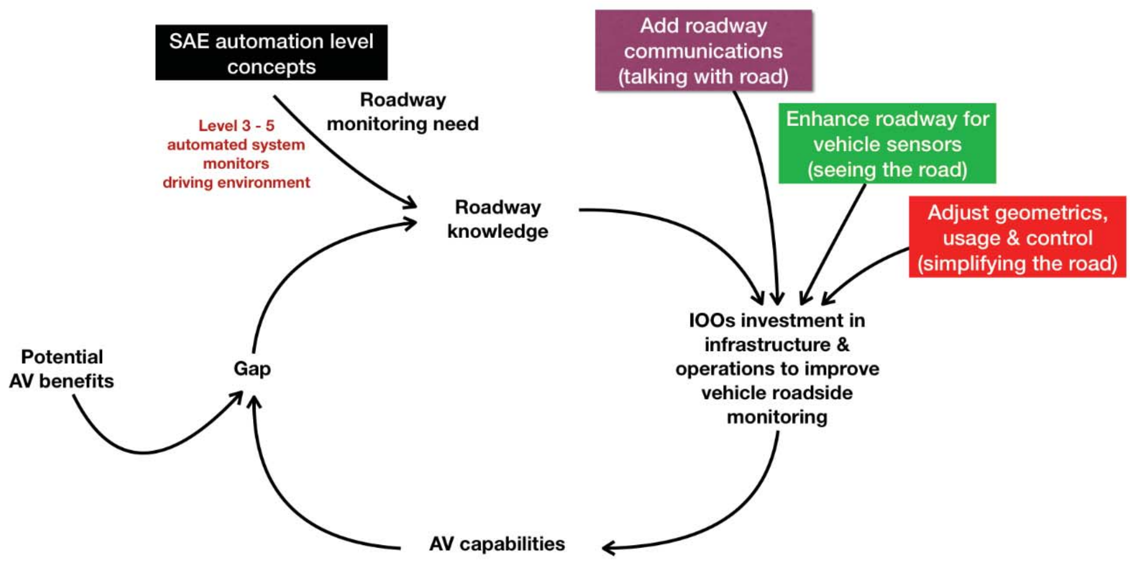

Figure 2. Role of Infrastructure Owners/Operators

WORKSHOP FINDINGS

A workshop was held as part of the NCHRP 20-24(112) CRCS Development project in Detroit, Michigan, on June 4, 2018, in conjunction with the 2018 ITS America Annual Meeting. This workshop brought together representatives from the infrastructure and automotive industry to discuss a CRCS framework for a future CAV environment.

The CRCS Development workshop attendees included a diverse set of stakeholders from the automotive industry, infrastructure industry (local/regional agency representatives, transit/toll authority representatives, and state DOT representatives), infrastructure providers, consultants, non-profit associations, and academia. The participants also represented geographic diversity across North America.

The following are inputs and key points identified by the participations from the interactive discussion and survey questions at the CRCS Development workshop:

- Using the SAE automation concept of roadside monitoring by the automated driving system, rather than humans.
- Conceptualizing the approach illustrated in the systems perspective of Figure 2.
- Using functional roadway classification terminology to identify the roadway types, if possible, and acknowledging that those classifications could be modified in the future as research and standardization move forward. An example of current research is NCHRP 855: Expanded Functional Classification.
- Embracing the IOO activities of:
    - <u>Talking</u>: adding communications.
    - <u>Seeing</u>: improving infrastructure recognition by vehicle sensors.
    - <u>Simplifying</u>: simplifying the environment for AVs.

Why Do We Need a CRCS?

The most commonly identified reasons for developing a CRCS according to the workshop participants were the following:

- To communicate effectively among stakeholders; create a common language.
- To support system interoperability and technology standardization.
- To assist investment, policy, and strategic decision-making.
- To help navigate gaps between and within stakeholders (variability in capability and maturity).

Some of the most frequent mentions from attendees were consistency, interoperable, and standardized.

How Would a CRCS Be Used?

The most commonly identified ways in which a CRCS would be used according to the workshop participants were as follows:

- For planning, project prioritization, and funding decisions.
- For identifying CAV infrastructure deployments that would support future V2I applications (e.g., weather, work zones, and sign information).
- For exploring data exchange and data quality needs for real-time and static data.
- For helping in framing the message for public awareness of infrastructure readiness with level of CAV capability in vehicles.

Some of the most frequent mentions from attendees were prioritization, planning, and data.

List One Key Attribute of a CRCS

Each workshop participant was asked to identify one key attribute they would like to see in a CRCS. The most common responses are as follows:

- Standardization across states.
- Standardized work zone information.
- Current road conditions (pavement, weather, traffic, incidents).
- Accommodation of future advancement of technologies/capabilities.

Some of the most frequent mentions from attendees were uniformity, common language, and quality.

Advice from Participants

At the end of the workshop, participants were asked to provide any additional advice. The most common responses were as follows:

- Keep it simple!
- Start with high level view and get consensus, then add detail.
- Don't worry about mapping to SAE levels.
- Define/clarify the audience—freeways, arterials, collector/local.

Some of the most frequent mentions from attendees were phased approach, simple, and transition.

Community Input

In addition to the workshop in Detroit, a session titled "Connected Roadway Classification System for Connected and Automated Transportation" was held at the ITS America annual meeting on June 5, 2018. Two NCHPR panel members and two representatives from the research team presented an overview of the CRCS workshop and initial findings. One of the major discussion topics at the session was the transportation community's familiarity with the CMM framework. This framework is used by many transportation agencies, and their staff have been trained on it for transportation operations.

Both the CRCS workshop and the ITS America annual meeting session provided opportunities for input. The input received during the Detroit meetings was as follows:

- Affirmed the concept shown in the systems perspective in Figure 2.
- Affirmed utility of talking, seeing, and simplifying as strategies to address roadway monitoring.
- Suggested there was no need to map to the SAE levels of automation.
- Recommended defining/clarifying the audience.
- Emphasized desire to use functional classification terminology to identify the roadway types if possible.
- Suggested adding a CMM structure similar to that embraced by the TSMO community.
- Recommended starting with high-level view and then adding detail.
- Suggested keeping the structure simple and implementable.
- Suggested revisiting it periodically, perhaps every 5 years.

NCHRP 20-24(112) Panel Input

The NCHRP 20-24(112) Panel reflects a diverse group of stakeholders from public agencies (ranging from state to local agencies) and private companies. A first step in building consensus on a CRCS is building consensus among the NCHRP panel guiding the project. The NCHRP 20-24(112) Panel was very involved in the CRCS workshop and made significant contributions to the workshop discussion. The following list highlights some additional input from the NCHRP panel:

- There is general agreement that the “talking,” “seeing,” and “simplifying” categories are easy to understand and reflect different infrastructure approaches.
- The CRCS should focus on the infrastructure elements (physical roadway and technologies) that are needed to support CAVs; it is too complicated to include operational scenarios and applications.
- IOOs need a foundational situational awareness of their roadway, telecommunications, and technology infrastructure and operations to deploy CAV infrastructure.
- A CRCS should accommodate entire roadways or designated lanes within a roadway right of way.
- A CRCS should accommodate emerging digital infrastructure.
- A CRCS should address security.
- A CRCS should be simple and implementable (a reiteration from the workshop).

FHWA Input

The research team conducted a webinar with FHWA staff involved in emerging technology, CAVs, policy, and highway safety. FHWA agreed with the approach of building from the CMM framework. There was additional support for the CRCS infrastructure approaches of talking, seeing, and simplifying the roadway. There was also agreement with the NCHRP panel’s recommendation of including IOO situational awareness of an agency’s current infrastructure and operation as a foundational step in preparing for CAV technologies. The discussion included how the CRCS framework could be applied at a project level, how the industry may be engaged in the development of the framework, and how to communicate the CRCS framework with the general public. The latter, which is important and will be needed in the future, is beyond the scope of the research project.

CRCS FRAMEWORK

The CMM is a structure that had its start in the software domain but has been adapted in other industries. It has been adapted for transportation and has been embraced by the TSMO community. The concept of a capability maturity framework emerged from the SHRP2 L01 and L06 projects that promoted a process-driven approach to improve TSMO (*15*).

CRCS WITH A CMM STYLE

For the CRCS framework, the research team adapted the structure of the matrix that is typically used to summarize the process. Figure 3, taken from a USDOT Fact Sheet (*16*), shows columns organized as follows:

- First column—a process dimension or topic (these become the rows of the matrix).
- Second column—a short “what is it” description.
- Columns three and beyond—a description of capabilities for each topic for specific capability levels.

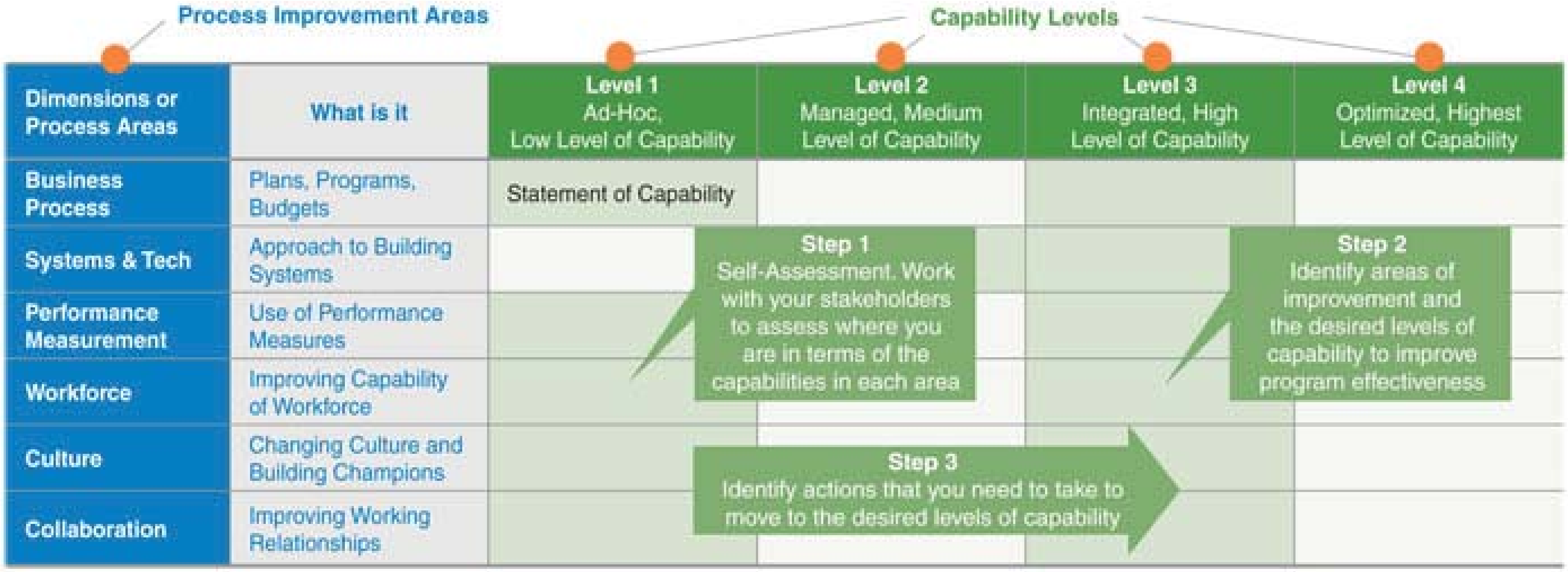

Figure 3. Capability Maturity Matrix Framework

The research team repurposed the CMM structure for a CRCS framework. Table 2 shows the structure. The structure displayed in Table 2 is similar to the CMM structure presented in Figure 3.

- First column—the process topics, or infrastructure approaches, of talking, seeing, and simplifying the road.
- Second column—a short "what is it" description of the infrastructure approach.

Columns three and beyond—a description of capabilities for each topic for four specific capability levels or classification levels.

Table 2. High-Level CRCS Framework

Infrastructure Approach	What It Is	Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1–5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	Statement of capability	Statement of capability	Statement of capability	Statement of capability
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	Statement of capability	Statement of capability	Statement of capability	Statement of capability
Simplifying	Design & operations for automated vehicles & their uses	Statement of capability	Statement of capability	Statement of capability	Statement of capability

The four descriptions of capabilities making up each classification level identified in Table 2 are:

- Needs upgrade and maintenance: Design or functionality that falls short of meeting existing guidance or recommendations for future technology accommodation.
- Meets current best practices: Design or functionality that meets existing guidance or recommendations for future technology accommodation.
- Meets emerging market (1–5 years): Design or functionality that supports early adoption of CV and AV applications or positions the roadway elements for communication/interaction with vehicles.
- Meets next decade market (10 years): Design or functionality that supports operation of most CV and AV applications and/or communicates/interacts with vehicles proactively.

Based on these four classification levels and the community feedback received, the research team identified trends that needed to be considered. First, not all IOOs have roadway segments that meet current best practices. Roadways, signs, and pavement markings age over time and need to be maintained, rehabilitated, and replaced. The infrastructure needs to be assessed, prioritized, and programmed for the improvements to meet current guidance, standards, or best practices as funding allows. The infrastructure elements that have degraded and need to be improved to meet current standards would fall into the "Needs Upgrade & Maintenance" column of Table 2. The segments of roadways that meet current standards and guidance would fall into the "Meets Current Best Practices" column of Table 2.

In addition, some regions are conducting early deployments, which represent the emerging markets. The CAV community is starting to gather knowledge on what should be installed to support these early deployments. The lessons from these early deployments on what the infrastructure should look like would fall into the "Meets Emerging Market" column of Table 2. Finally, there are projections as to the future of vehicle and infrastructure design and functionality in the next 10 years. As consensus builds around the next wave of technology development, that infrastructure would make up the "Meets Market 1st Growth Decade" column of Table 2. It was felt that the industry does not have confidence in the likely scenarios beyond 10 years; thus, it would be highly speculative to include a classification beyond 10 years.

Guidance for the CRCS Cells

Following the CMM structure, the CRCS framework includes cells for each of the classification levels. For each infrastructure approach (i.e., row), there would exist criteria within each cell for the different CRCS classification levels. As shown in Table 3, individual cells would have capability criteria defined that allow IOOs to understand the roadway infrastructure an IOO should consider for an individual road or a system of roads to meet a corresponding classification.

Table 3. Classification Criteria by Infrastructure Approach

Infrastructure Approach	What It Is	Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1–5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	T1	T2	T3	T4
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	S1	S2	S3	S4
Simplifying	Design & operations for AV vehicles & their uses	M1	M2	M3	M4

CRCS Development

Building on the CMM structure, the research team developed a high-level CRCS framework. The guiding input that led to the CRCS framework includes:

- Recognizing that the SAE levels of driving automation describe a role for IOOs—adding value by enhancing the vehicle's ability to monitor the roadway.
- Structuring the actions that an IOO could pursue to add roadway communications (talking with the road); enhance the roadway for vehicle sensors (seeing the road); and adjust geometrics, usage, and control of the roadway (simplifying the road).
- Identifying the path that these concepts can play in closing the gap between automated expectations and results.
- Formulating the CRCS in a familiar CMM structure that can be revisited as the market matures.

IOO Situational Awareness

Another foundational step for IOOs is creating situational awareness of their roadway and technology infrastructure. IOOs should have good documentation on their physical and digital assets, should be collecting and storing data to support CAV applications, and should be involved in transportation system management and operational activities. Examples of these include:

- Physical assets.
    - Roadway geometrics, bridge heights, signs, pavement markings, traffic signal controls, ITS equipment, fiber, RSUs.
- Digital assets.
    - GIS, LIDAR, high-definition maps, roadway as-builts.
- Data.
    - Traffic detection (volumes, speeds, travel times).
    - Traffic signal controller (ATSPM, SPaT).
    - Work zones, incidents, weather.
- TSMO.
    - Individual agency or regional transportation management center operations.
    - Advanced transportation management systems, advanced transportation information systems, road weather information systems, incident management, managed lanes, ramp metering, active traffic management, integrated corridor management, traffic-responsive or traffic-adaptive traffic signal operations.

State of the CAV/Infrastructure Knowledge

The criteria and capabilities at each CRCS level across the different infrastructure approaches are dependent on the industry knowledge about how infrastructure supports CAV safety and operation. Table 4 presents a snapshot of current knowledge about technologies, the marketplace, and infrastructure. The green circles in the "Needs Upgrade & Maintenance" and "Meets Current Best Practices" columns of Table 4 indicate where there is significant knowledge about current communications, use of traffic control devices, and geometric design of roadways.

In the "Meets Emerging Market" column of Table 4, there is more discrepancy in knowledge. More knowledge is emerging on the pavement marking and signing needed for AVs to define criteria for seeing the road. There is also evolving knowledge about the connectivity needed to support V2I applications. However, there is still uncertainty about the communication that will be available in passenger cars and trucks since technology is still competing in the marketplace. Even less is known about how the roadway design should be changed to improve CAV safety and operation. Some AV operations are limited to only controlled-access facilities or low-speed campus environments without mixed traffic as methods of simplifying the operational design domain.

Table 4. State of Knowledge about Infrastructure Impact on CAVs

Infrastructure Approach	What It Is	Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1–5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	T1	T2	T3	T4
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	S1	S2	S3	S4
Simplifying	Design & operations for AV vehicles & their uses	M1	M2	M3	M4

Legend:

- Green circle means there is significant knowledge and certainty.
- Yellow triangle means that enough research has occurred for some deployment. Uncertainty remains until the marketplace further matures.
- Red square means that significant uncertainty exists.

CRCS RECOMMENDATION

Tables 5–10 present the recommended infrastructure approaches, classification levels, and criteria within each level for the CRCS, as well as resources that will inform the CRCS as it evolves in the future.

Talking to the Road—Connectivity

For each of the infrastructure approaches, there are more detailed definitions of the classification levels. The definitions of the classification levels for the "talking to the road" infrastructure approach are as follows:

- <u>Needs upgrade and maintenance</u>: No wireless or wireline communication in the roadway corridor. Infrastructure elements (such as a traffic signal) serve the basic function, but the technology is out of date or is in need of maintenance.
- <u>Meets current best practices</u>: The infrastructure element functions with current technology and provides functionality consistent with today's best practices for TSMO and supports regional operations.
- <u>Meets emerging market (1–5 years)</u>: The infrastructure element provides additional functionality to support emerging CV/AV services such as providing a SPaT message or other V2I communication.
- <u>Meets next decade growth (10 years)</u>: The infrastructure element includes technology that provides a migration path for future technology applications and communication methods.

The "talking to the road" approach in Table 5 focuses on the connectivity between vehicles and the roadside. It does not specify the technology (i.e., cellular versus DSRC) but identifies the criteria for V2I capability. The roadway infrastructure may include DSRC RSUs or appropriate cellular equipment and coverage. The "seeing the road" approach in Table 5 focuses on signs and markings. The "simplifying the road" approach in Table 5 focuses on meeting geometry design guidance.

Table 5. CRCS Criteria for Talking to the Road

Infrastructure Approach	Infrastructure Element	CRCS Assessment Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Talking Electronic communications between vehicles & roadway	Roadway	No wireline or wireless communication ability	Fiber communication along roadway with access points. Good cellular coverage in corridor	DSRC or C-V2X nodes tied into fiber backbone.	Small cells deployed in roadway right-of-way with good 5G coverage and connection to fiber backbone.
	Traffic Signals	Signal meets MUTCD but internal technology is outdated; no connection	Signal meets MUTCD and is ~~a~~ current technology; signal is part of a connected system	Signal is equipped with V2I communication capability (either DSRC or cellular)	Signal transmits SPaT messages
	Roadside Devices (ITS equipment, DMS, sensors, etc.)	No or limited roadside devices with no communication capability	ITS Equipment (DMS, sensors, ITS cabinets) are tied to fiber backbone or have cellular capability to communicate to TMC.	Infrastructure element is also equipped with capability to communicate over DSRC or C-V2X	Infrastructure element communicates information on conditions and performance with local processing capability
	Temporary traffic control devices (Cones, barricades, portable DMS)	Traffic control devices are deployed with no communication capability	Temporary traffic control devices are equipped with cellular communication capability	Portable infrastructure element is equipped with technology that has the capability to communicate	Portable infrastructure element communicates information on conditions and performance

The greatest amount of knowledge on how infrastructure impacts CAV operations is developing in the classification level "meets emerging market." The cells in the CRCS table will require period updates in the fast-changing transportation marketplace. Table 6 provides resources that will inform the knowledge base that is evolving.

Table 6. Talking to the Road Resources

Need Categories	Resource	When	Note
Equipment - experience by IOOs	SPaT Challenge	Deployment in 50 states at 20 intersections by 2020	
Equipment - Deployment capability (specs, testing plans, etc)	SPaT Challenge resource documents	Being populated now on National Operations Center of Excellence website	https://transportationops.org/spatchallenge/resources
Applications - initial apps developed with OEMs & IOOs	CAT V2I Deployment Coalition IOO/OEM Forum priorities	Circa 2020 - Red light running	Others in process
Institutional readiness - enabling legislation	National Conference of State Legislatures (NCSL) – tracking of legislation		
Standards	SAE J2735 Basic Safety Message	SAE J2735 available now.	

Seeing the Road—Monitoring and Sensing

The definitions of the classification levels for the "seeing the road" infrastructure approach are as follows:

- Needs upgrade and maintenance: The infrastructure element (such as signs and markings) serves its basic function but may lack desired visibility for the human eye and be in need of maintenance based on retroreflectivity guidance.
- Meets current best practices: The infrastructure element provides visibility consistent with today's retroreflectivity standards and best practices for visibility for the human eye.
- Meets emerging market (1–5 years): The infrastructure element provides visibility needed to support emerging technologies such as providing readability for CVs/AVs. This may exceed today's standards/guidelines in order to be "read" by vehicle sensors.
- Meets next decade growth (10 years): The infrastructure element includes technology that provides a migration path for future technologies and communication methods.

The "seeing the road" infrastructure approach in Table 7 focuses on how sensor systems (i.e., machine vision, LIDAR, etc.) interpret the driving environment and what can be done by IOOs to maintain and enhance the roadway, signs, pavement markings, and traffic signals to be easily sensed by these technologies.

Table 7. CRCS Criteria for Seeing the Road

Infrastructure Approach	Infrastructure Element	CRCS Assessment Levels: Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Seeing Infrastructure (e.g., signs & markings) readable by vehicle sensors	Roadway	Roadway assets are not recorded in digital form	Digital inventory of roadway assets exist	Major corridors or areas have digital maps.	All roadways are digitally mapped.
	Signs	Signs may not be present or if they are present may lack desired visibility based on retroreflectivity guidance	Signs meet desired visibility based on retroreflectivity guidance	Signs provide visibility needed for CV/AV recognition	Signs include technology that provide for future machine visibility and processing
	Marking	Markings may not be present or, if they are present may lack desired visibility based on retroreflectivity guidance ; Markings are not present	Markings meet desired visibility based on retroreflectivity guidance ; Markings are present.	Markings are present and consistent (lane and edge lines) and provide visibility needed for CV/AV recognition in terms of reflectivity and contrast.	Markings include technology that provide for future machine visibility and processing
	Traffic Signals	Traffic signals are in need of upgrade or maintenance.	Traffic signal equipment meets MUTCD requirements	Signal heads are consistent in design and use of technology. Use of back plates to eliminate glare. Removal of all visual obstructions.	Research is needed

Similar to the connectivity, the design of the infrastructure to accommodate infrastructure readability by vehicle sensors is still evolving. Table 8 provides some resources that will feed into the next update to the CRCS.

Table 8. Seeing the Road Resources

Need Categories	Resource	When	Note
Equipment – Vehicles and Infrastructure	ATTSA – Evaluation of Pavement Marking Width on Detectability By Machine Vision	2018	Report looks at 4-inch versus 6-inch markings
	NCHRP 20-102(06) – Road Markings for Machine Vision	Publication due in 2019	Report looks at Machine Vision performance for various road marking use cases
Deployment capability (specs, testing plans, etc.)	NCUTCD CAV Task Force	2019	TCD suggestions for automated driving systems
	NCUTCD Task Force on Traffic Signals	2020	Develop AV readiness checklist
Applications - initial applications developed with OEMs & IOOs	None at this time		
Institutional Readiness - enabling legislation	National Strategy for Highway Automation (AASHTO Task Force on Highway Automation)	2019/2020	Seeking inclusion in next transportation bill reauthorization.
Standards	MUTCD Part 3 - Markings	Balloting in 2019	

Simplifying the Road—Designing for AVs

The definitions of the classification levels for the "simplifying the road" infrastructure approach are as follows:

- Needs upgrade and maintenance: The infrastructure geometry is challenging and may not meet AASHTO Green Book recommended guidance.
- Meets current best practices: The infrastructure meets AASHTO Green Book standards.
- Meets emerging market (1–5 years): The infrastructure is designed with sensitivity to navigational needs of CVs/AVs and makes accommodation for those needs.
- Meets next decade growth (10 years): The infrastructure is specifically designed to accommodate navigational and operations needs of CVs/AVs.

The "simplifying the road" infrastructure approach in Table 9 focuses on how IOOs can design or control the use and operation of a roadway to improve the operation of CVs and AVs. The infrastructure is further broken down into the roadway, temporary roadway geometry, low-speed environments, and dedicated facilities.

Table 9. CRCS Criteria for Simplifying the Road

Infrastructure Approch	Infrastructure Element	CRCS Assessment Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Simplify Design & operations for AV vehicles & their uses	Roadway	Infrastructure geometry may not meet AASHTO guidelines. Pavement in poor condition.	Infrastructure geometry meets AASHTO guidelines. At least one full shoulder. No pavement defects.	Infrastructure geometry is designed to facilitate navigation by CV/AVs	Infrastructure geometry is specifically designed to accommodate navigation and operation of CV/AVs
	Temporary Roadway Geometry (work zones, utility zones)	Minimal navigational aids (cones, barricades, etc.) are available to define temporary geometry	Navigational aids (cones, barricades, etc.) for temporary geometry are in compliance with the MUTCD	Navigational aids (cones, barricades, etc.) for temporary geometry are in compliance with the MUTCD and are equipped with communication technology for V2I and are designed to be visible for CAVs	Navigational aids (cones, barricades, etc.) for temporary geometric changes communicate with vehicles and are designed to support CAV navigation and operations
	Low-speed Environments	No designation of zone or district for CAVs.	Infrastructure geometry meets design guidance and traffic control devices meet MUTCD.	Research is Needed	Research is Needed
	Dedicated Facilities	No designation for a dedicated CAV facility.	Managed lanes that have user requirements for access.	Research is Needed	Research is Needed

Controlling the ODD by simplifying the geometry or changing the use, operation, or rules of the road is the least well understood infrastructure approach. More experience is needed to gather how simplifying these driving environments will improve CV and AV operation. Table 10 provides some resources that will feed into the next update to the CRCS.

Table 10. Simplifying the Road Resources

Need Categories	Resource	When	Note
Equipment – Vehicles and Infrastructure	NCHRP 20-102(21) – Infrastructure Modifications to Improve the Operation Domain of AVs	In development	Relates to simplifying the ODD for AV operations
	NCHPR 20-102(24) – Infrastructure Enablers for CAVs and Shared Mobility	In development	Relates to infrastructure to help CAVs talk and see the road
	NCHRP 29-24(102) – Readiness Framework: Coast-to-Coast Automated Mobility by 2025	In development	Relates to addressing AV readiness
Deployment capability (specs, testing plans, etc)	None available		
Applications - initial applications developed with OEMs & IOOs	USDOT Report – Low-Speed Automated Shuttles: State of the Practice	2018	Provides examples of the ODDs with AV deployments
Institutional Readiness - enabling legislation	NCHRP Report 891 – Dedicating Lanes for Priority or Exclusive Use by CAVs	2018	Reviews laws and regulation regarding dedicated lanes
Standards	No specific standards for these ODDs		

APPLYING THE CRCS

The CRCS framework is flexible enough to accommodate various needs and uses. Based on the CRCS workshop and community input, the research team envisions that IOOs will be the primary users of the CRCS. These IOOs may be state DOTs, regional agencies, local agencies, or private entities (e.g., private toll operators). Uses could include benchmarking the IOOs in terms of the maturity of their roadways to support CAVs, quantifying the roadways or a network of roadways for their capability to support CAVs, or programming investments to advance roadways to higher classifications of CRCS levels.

In addition, IOOs may be interested in classifying their roadways based on one of the infrastructure approaches or a combination of two or all three approaches. Based on the goals and objectives of their agency, they may want to apply the CRCS to one or more of the infrastructure approaches. For example, an agency may put high emphasis on sharing traffic signal phase and timing data with vehicles equipped to receive the data. That IOO may choose to focus on the first infrastructure approach of talking with the road. Alternatively, an IOO may be cautious about the implications of various communications technologies and thus may choose to focus more on ensuring that pavement marking and signing is at the highest level to support AV operation. Furthermore, an IOO may want to set a benchmark on its status on all approaches and conduct a comprehensive assessment.

The following sections provide examples of how the CRCS framework could be applied to the CDOT CRCS, an automotive company's technology deployment, and an IOO's assessment of its roadway network.

CDOT Classification of Roadways

One of the challenges facing IOOs is the level to which they intend to equip their roadways for the impending rollout of CVs and AVs. Recognizing this, CDOT proposed a road classification system with six levels that relate to the roadway's ability to support operations, ITS, and CVs and AVs. The six levels are presented again below:

- Level 1: Unpaved and/or non-striped roads are designed to a minimum level of standard of safety and mobility.
- Level 2: Paved roads are designed to the AASHTO guidance and pavement markings and signing meeting the MUTCD standards. ITS equipment or infrastructure is not available to collect connected vehicle data. Access to cellular data service may be available.
- Level 3: There is ITS equipment operated by a TOC, one-way electronic data share between DOT/vehicle/user, and/or mixed-use lanes.
- Level 4: Roadway or specific lane has adaptive ITS equipment (i.e., smart signals hold for vehicles, highway lighting turns on for vehicles, etc.) with TOC override only; two-way data share exists between DOT/vehicle/user; and/or lanes are designated for vehicle Levels 3 and 4 only.
- Level 5: (Advance guideway system) roadway or specific lane is designed for vehicle Level 4 only with additional features that may include inductive charging, advanced/enhanced data sharing, and so forth. No roadside signs are needed since all roadway information is direct to vehicles' on-board systems.
- Level 6: All lanes on the roadway are designed for only vehicle Level 4 systems—no signs, signals, striping needed.

Because CDOT has invested effort into developing its CRCS, the research team wanted to ensure that it could be accommodated within the CRCS framework. The CRCS framework would support CDOT in continuing to use its definitions but further expand its levels across the infrastructure approaches. The CDOT levels within the CRCS framework would be as follows:

- Needs Upgrade and Maintenance.
    - CDOT Level 1—unpaved roads, roads with little to no communication or traffic control devices, and roads with degraded infrastructure in need of upgrades or maintenance.
- Meets Best Practices.
    - CDOT Level 2—roads that meet current AASHTO and MUTCD guidance.
    - CDOT Level 3—roads that include mature ITS systems with connectivity to ITS equipment and active traffic control devices to support operations.
- Meets Emerging Market (2023).
    - CDOT Level 4—roadways that have DSRC or C-V2X connectivity deployed to support V2I applications.

- Meets Market 1st Growth Decade.
  - CDOT Level 5—mature CAV infrastructure that supports SAE Level 4 and 5 automation and allows removal of traffic control devices on select roadways.
  - CDOT Level 6—mature CAV infrastructure that supports SAE Level 4 and 5 automation and allows removal of traffic control devices on all roadways.

Table 11 shows how the CDOT CRCS maps to the CRCS framework.

Table 11. Colorado CRCS in CRCS Framework

Infrastructure Approach	What It Is	CRCS Capability Levels for Colorado DOT CRCS Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	T1 CDOT Level 1	T2 CDOT Level 2 CDOT Level 3	T3 CDOT Level 4	T4 CDOT Level 5 CDOT Level 6
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	S1 CDOT Level 1	S2 CDOT Level 2 CDOT Level 3	S3 CDOT Level 4	S4 CDOT Level 5 CDOT Level 6
Simplifying	Design & operations for AV vehicles & their uses	M1 CDOT Level 1	M2 CDOT Level 2	M3 CDOT Level 4	M4 CDOT Level 5 CDOT Level 6

Automotive Industry Classification of Roadways

Today, the marketplace is bringing forward significant capabilities and beginning to classify roadways along with their products. That is, companies are branding their vehicle models' capabilities and the roadways on which they operate. For example, GM Cadillac is delivering a driver assistance technology called Super Cruise™ and classifying roadways that are Super Cruise™ freeways (*17*). Operation within these geofenced areas will still be dependent on roadway characteristics such as the visibility of lane markings to the sensors (*18*). Figure 4 shows the roadway network published by GM where its Cadillac Super Cruise™ system functions. These roadways are largely part of the interstate system and include gaps where the roadway is under construction or GM does not have the high-definition maps fully available to engage its Super Cruise™ system.

Figure 4. Super Cruise™ Freeways

Using the CRCS framework, Cadillac Super Cruise™ is relying on seeing the road and simplifying the road. That is, the Cadillac Super Cruise™ system is relying on IOOs to have the pavement markings and signing that meet the best industry practices and is simplifying the driving environment by limiting Cadillac Super Cruise™ operation to only controlled-access interstate highways. Where this functionality falls on the CRCS framework is shown in Table 12. The Cadillac Super Cruise™ system is not relying on connectivity directly with the roadway infrastructure, nor is it expecting roadway infrastructure to be designed with functionality beyond current MUTCD practices. Thus, it does not expect any infrastructure deployment that would be classified as “meets emerging market.” The CRCS framework does allow for discussions between the automotive industry and IOOs on what could improve the operation of the Cadillac Super Cruise™ system. Agreement on those elements could generate new criteria that could be expanded into the “Meets Emerging Market” column of Table 12.

Table 12. Cadillac Super Cruise™ System in CRCS Framework

Infrastructure Approach	What It Is	CRCS Capability Levels for Super Cruise ™ Interstates			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	T1	T2	T3	T4
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	S1	S2 Super Cruise ™	S3	S4
Simplifying	Design & operations for AV vehicles & their uses	M1	M2 Super Cruise ™	M3	M4

Infrastructure Owners/Operators

Another application of the CRCS framework could be the development by an IOO of reports or charts characterizing its roadway status to support CAV operation. Similar to the CDOT CRCS, a color-coded map could be produced that identifies the classification levels on each segment of roadway. In addition to a color-coded map, an IOO might show readiness in a city region (or other jurisdictional area such as MPO region or state DOT district) by percent of roadway or roadway network meeting any of the classification levels. Table 13 shows how this chart might be configured for a specific region or network of roadways. Furthermore, a summary such as that illustrated in Table 13 could be done by roadway functional type. That is, one table could show percent for freeways, another show percent for arterials, and a third show percent for local streets.

Table 13. CRCS Template for IOO Condition Report

Infrastructure Approach	What It Is	Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1–5 years)	Meets Next Decade Market (10 years)
Talking	Electronic communications between vehicles & roadway	T1 XX%	T2 XX%	T3 XX%	T4 XX%
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	S1 XX%	S2 XX%	S3 XX%	S4 XX%
Simplifying	Design & operations for AV vehicles & their uses	M1 XX%	M2 XX%	M3 XX%	M4 XX%

MAINTAINING THE CRCS

Even with some uncertainty about the direction of the CAV industry, there are efforts in place that will continue to inform the process. Professional societies such as AASHTO, Institute of Transportation Engineers (ITE), and ITS America have committees and working groups focusing on policy, planning, and deployment issues. In addition, USDOT, TRB, and individual states are conducting research related to CAVs. The outcomes from these research efforts can inform the CRCS framework. Figure 5 provides examples of how some of the efforts can inform the infrastructure approaches in the CRCS framework.

For example, the Connected and Automated Transportation (CAT) Coalition supported by AASHTO, ITE, and ITS America has a V2I working group supporting the SPaT Challenge. Knowledge gained from the SPaT Challenge will inform the "talking to roads" approach by further defining best practices and emerging markets from early deployments. In addition, TRB is funding research through NCHRP 20-102 Task 6 that is looking at the performance of AV machine vision systems on sensing colored (i.e., white vs. yellow) and patterned (i.e., solid vs. dashed) pavement markings under different lighting and pavement conditions. These research findings will inform the "seeing the road" approach by defining the emerging best practices for pavement marking infrastructure to support AV safety and operation. Last, the CAT Coalition also has an AV group working on CAV deployment scenarios that may inform policy on the design, use, and control of roadways.

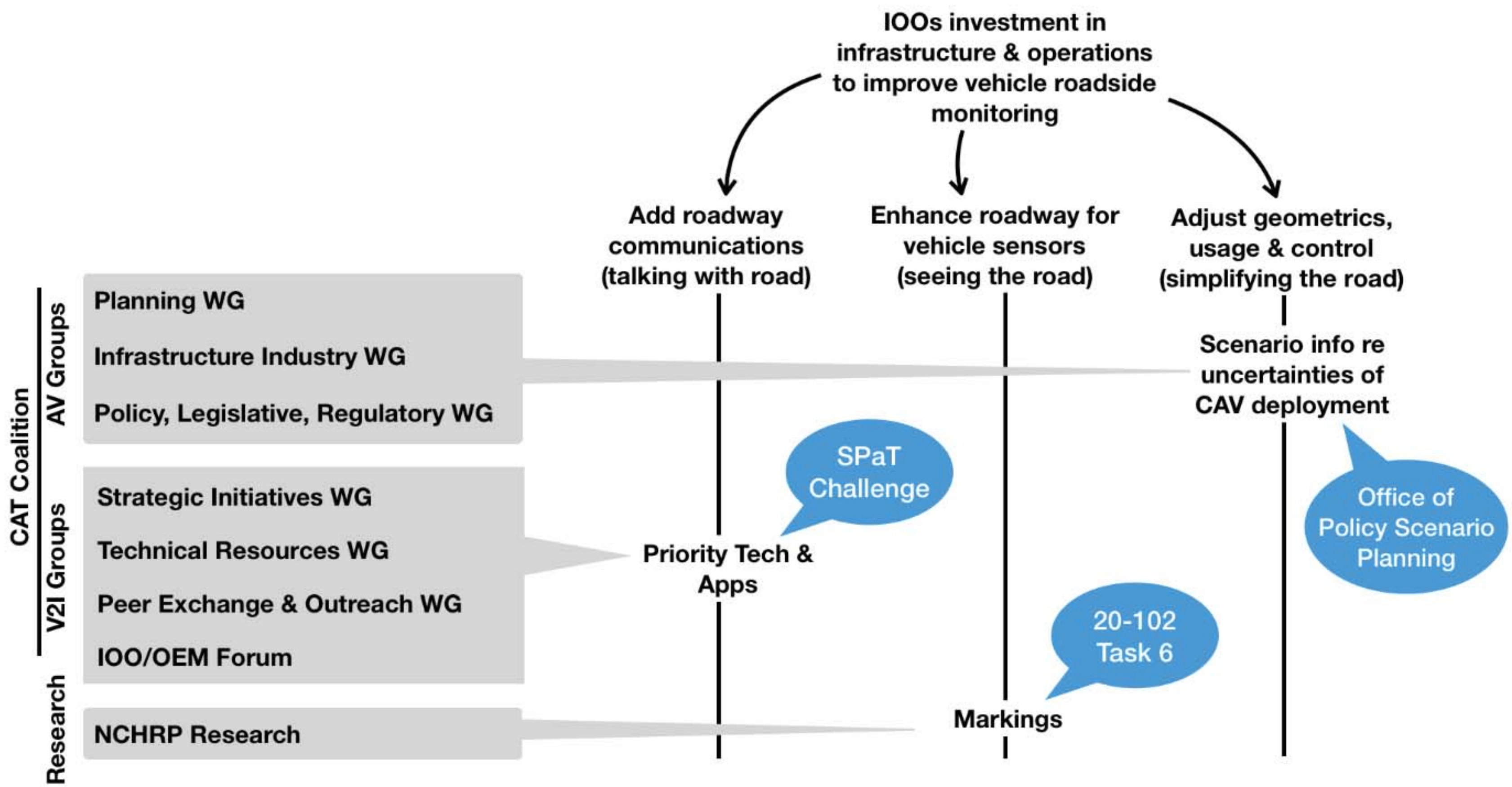

Figure 5. Example Activities in Each CRCS CMM Process Area

Why Update

An important characteristic of an effective CRCS is that it is relevant for the capabilities of vehicles and travelers using the roadway. The roadway infrastructure needed for safe and efficient operation of CVs and AVs is evolving as more knowledge is exchanged between the automotive industry and IOOs.

At this time, the transportation industry is still charting its course and grappling with many automated and connectivity issues. There is limited experience by all stakeholders. The long-term infrastructure needs for CVs, AVs, IOOs, and travelers are unknown. The future market delivery of technology and public adoption of those technologies and services is still unknown. Given this environment, the CRCS needs to evolve as the vehicle technologies evolve. The objective should be to keep the CRCS updated to reflect new and emerging knowledge.

When to Update

The CRCS approach is based on looking ahead at time intervals that have varying levels of certainty. The first forward-looking time period is 1–5 years, the expected time when the emerging market will more fully disclose its needs. Demonstrations and pilot projects will reveal the needs of vehicles and travelers and what infrastructure solutions may meet those needs. The second forward-looking time period is the end of the next decade, a 10-year horizon. There is less certainty of the needs in 10 years than in the next 5 years. As vehicle technologies evolve and vehicle experience is gained with operating on enhanced infrastructure, new needs may emerge or existing needs may diminish. The CRCS framework will need to be adjusted accordingly.

Therefore, the CRCS should be revisited and updated at the end of the first time period, when the marketplace needs are first emerging. The NCHRP 20-24(112) research team recommends the next update be in 5 years when the first emerging market wave of CVs occurs and much of the current research will be concluded and made publically available. That update in 5 years can build on the experience of all stakeholders and leverage the exposed marketplace needs.

Who Updates

The CRCS will hopefully be adopted by IOOs as a way to assess the readiness of their infrastructure to support CVs and AVs. There are, and will be, many entities with vested interests in the interactions between the roadway, vehicles, and travelers. The dynamics of how these interests are represented and resolved should be addressed in transparent and neutral venues. Forums for this engagement include the following:

- Automotive groups including the Automotive Industry Action Group and Crash Avoidance Metric Partnership.
- Standards groups including SAE and the Institute of Electrical and Electronics Engineers.
- Infrastructure owner-operator groups such as AASHTO, ITE, American Public Transportation Association, and National Committee on Uniform Traffic Control Devices.

- Cross-cutting groups such as ITS America.
- Research groups such as TRB/NCHRP and state DOT research departments.

However the open, transparent, and neutral approaches are pursued, they should consider engaging affected constituencies such as international CRCS groups, regulators, and legislative bodies.

What Gets Updated

To begin the update and provide the background information for the work, a description of the current state of the practice should be developed. The state of the practice should include research results, findings from various professional group task forces, and updates to any guidance and standards documents (e.g., MUTCD). This synthesis will help ensure that all relevant views and constituencies are identified. The effort should include an inventory of the use of the CRCS framework defined through this NCHRP project and lessons learned from various IOOs in their assessments. The update should also reflect any further development of other CRCS frameworks, either by groups within the United States or by those outside the United States. The only known international effort is the INFRAMIX project discussed in Chapter 2 of this report. The update should also reflect the viewpoints of stakeholders on the technologies, marketplace conditions and trends, infrastructure status, and CRCS capabilities.

How to Implement Updates

Gaining acceptance and encouraging use of the CRCS is key to aligning implementation of the infrastructure with the needs of CAVs. The update should examine how key infrastructure activities including planning, design, construction, and operation are linked to the CRCS. This activity could include development of guiding principles describing how key documents reference the CRCS capabilities. These documents could include the MUTCD and the AASHTO Green Book.

CHAPTER 4. CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

CONCLUSIONS

The CRCS Development project was successful in bringing together a diverse set of stakeholders from the automotive industry, infrastructure industry (local/regional agency representatives, transit/toll authority representatives, and state DOT representatives), infrastructure providers, consultants, and academia that also represented geographic diversity in North America. These stakeholders provided valuable input on how to develop a CRCS framework, what should be included within the framework, and how to use the framework.

Researchers introduced three approaches to classifying improvements to the infrastructure: talking to the road, seeing the road, and simplifying the road. IOOs can enhance the infrastructure to improve how CVs and AVs connect to the roadway or sense the roadway. IOOs can also simplify the roadway ODD to enhance AV performance. The community of industry stakeholders (i.e., workshop participants, panel members, and key stakeholders) affirmed these approaches as ways to classify improved infrastructure to support both connectivity and automation.

One recurring response from the industry stakeholders was to keep any future CRCS simple and implementable. Simplicity includes the classification levels and criteria for classification. If the CRCS is not simple, it will not be adopted and used by agencies across the country (and potentially internationally). Simplicity also reflects the level of effort to implement or use a CRCS. Many comments from the workshop participants centered on using the CRCS to guide planning, investment, and deployment. For a CRCS to be used by a wide variety of users, it must be straightforward and direct in application.

A conclusion drawn from industry stakeholder feedback was to revisit the CRCS periodically. This recommendation recognizes that technology (both vehicle and infrastructure) and research findings evolve over time. The advances in technology and completed research should be included in future revisions to a CRCS. An approach for how to conduct this update is provided in Chapter 4 of this report.

Another conclusion was to separate roadway infrastructure from the applications. The CRCS should focus on how to classify roads by where and what infrastructure is deployed, but not classify roads by which applications are deployed. As can be seen from the tables in Chapter 3, the discussions included infrastructure elements and applications. Infrastructure elements include geometric features (i.e., type of intersection, cross section, and work zones), type and condition of traffic control devices (i.e., signs and markings), and presence of telecommunications (i.e., fiber, DSRC radios). Some of the applications referred to include transit signal priority, weather warnings, and work zone alerts. The recommendation is to focus on classifying roadways by the infrastructure deployed to support vehicle automation and V2V/V2I applications, but not make the CRCS dependent on what applications are enabled on any specific roadway.

RECOMMENDATIONS

The CRCS framework is envisioned to provide a common tool that can be used by a variety of users in a consistent method. However, it is also structured to be flexible and allow for iterative updates as the industry gains new knowledge. At this time, it is recommended that the framework be revisited on a 5-year cycle. This would allow for the inclusion of evolving best practices and new research findings in the CRCS criteria for the different cells. A 5-year cycle would also allow for revisiting the CRCS capability levels (i.e., framework columns) to assess if the four columns are still appropriate and if any changes or additions are needed.

The following recommendations are summarized from this report:

- IOOs should conduct a situational awareness assessment of their infrastructure and systems.
- Agencies should use the recommended CRCS and apply it to their roadway system.
- TRB/AASHTO should continue to map current research and problem statements to the gaps in the CRCS knowledge base.

SUGGESTED RESEARCH

The following areas of research are suggested to contribute to the knowledge base that will assist in future updates of the CRCS:

- AV sensor performance under a greater range of pavement marking conditions should be examined. There is research emerging on the performance of machine vision systems' ability to accurately read solid versus broken lines, yellow versus white lines, lines under daytime versus nighttime conditions, and lines under wet and dry pavement conditions.
- Best practices for establishing AV readiness for pavement markings should be reviewed. More knowledge is needed on how to combine the measurements of retroreflectivity, contrast, and presence of pavement markings into a quantitative or qualitative measure of AV readiness.
- Similar to pavement markings, more knowledge is needed on how AV sensor systems see traffic signals. How does the bulb technology, lens size, signal head placement, and use of back planes to reduce glare affect a sensor's ability to accurately read the signal indication?
- This project focused on a CRCS to communicate with a CV and AV industry. More research on how to communicate infrastructure needs to the public would benefit IOOs in linking their infrastructure investments with the public's perception of the emerging technology market.

REFERENCES

1 SAE International, J3016, *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, June 2018.

2 U.S. Department of Transportation, *Preparing for the Future of Transportation—Automated Vehicles 3.0*, October 2018.

3 American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*, Washington, D.C., 7th Edition, 2018.

4 N. Stamatiadis, A. Kirk, D. Hartman, J. Jasper, S. Wright, M. King, and R. Chellman, NCHRP Research Report 855, *An Expanded Functional Classification System for Highways and Streets*, Transportation Research Board, Washington, D.C., 2018.

5 Beverly Kuhn, Business Process Frameworks for Transportation Operations, https://ops.fhwa.dot.gov/tsmoframeworktool/index.htm. Accessed on July 25, 2019.

6 D. Gettman, L. Burgess, D. Haase, E. Flanigan, and S. Lockwood, *Guidelines for Applying Capability Maturity Model Analysis to Connected and Automated Vehicle Deployment*. FHWA. 2017.

7 INFRAMIX, Objectives, https://www.inframix.eu/objectives/. Accessed on July 25, 2019.

8 A. Carreras, X. Daura, J. Erhart, and S. Ruehrup, "Road Infrastructure Support Levels for Automated Driving," EU-TP1488, ITS World Congress, Copenhagen, Denmark, September 2018.

9 S. Manganiaris, "Infrastructure Classification Scheme to Support the Circulation of Automated Vehicles," Presented at 47th ASECAP Study and Information Days, Costa Navarino, Messinia, Greece, May 2019.

10 WisDOT Traffic Operations Infrastructure Plan, Bureau of Highway Operations Wisconsin Department of Transportation, 2008.

11 I. Tang and T. P. Breckon, Automatic Road Environment Classification. *IEEE Transactions on Intelligent Transportation Systems*, 2011, Vol. 12, No. 2: 479–484.

12 Q. Zhu, L. Chen, Q. Li, M. Li, A. Nüchter, and J. Wang, "3D LIDAR Point Cloud Based Intersection Recognition for Autonomous Driving," 2012 Intelligent Vehicles Symposium, Alcalá de Henares, Spain, 2012.

13 C. Johnson, *Readiness of the Road Network for Connected and Autonomous Vehicles*, Royal Automobile Club Foundation for Motoring Ltd., 2017.

14 S. Lawson, *Roads that Cars Can Read: Report III—Tackling the Transition to Automated Vehicles*, June 2018.

15 Capability Maturity Frameworks for Transportation Systems Management and Operations (TSM&O) Program Areas, FHWA 2016, https://ops.fhwa.dot.gov/publications/fhwahop16031/index.htm

16 Capability Maturity Frameworks for Transportation Systems Management and Operations (TSM&O) Program Areas: Fact Sheet, FHWA 2016, https://ops.fhwa.dot.gov/publications/fhwahop16031/fhwahop16031.pdf

17 Introducing Cadillac Super Cruise, http://www.cadillac.com/world-of-cadillac/innovation/super-cruise

18 Super Cruise™, http://www.cadillac.com/ownership/vehicle-technology/super-cruise