Connected Traffic Control System (CTCS): Research Planning and Concept Development

Task 5: Research Plan

Final

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1   INTRODUCTION

The University of Virginia Center for Transportation Studies (CTS), on behalf of the Connected Vehicle Pooled Fund Study (CV PFS) and the United States Department of Transportation (USDOT), is working towards advancing Multi-Modal Intelligent Traffic Signal System (MMITSS) research efforts to develop Connected Traffic Control System (CTCS) concepts, concepts that span beyond a few signalized intersections to consider entire signalized corridors and their connections to the freeway system. This desire and effort have led to a series of work products including this roadmap for future research. This document presents a CTCS research plan based upon previous work that focuses on ten potential applications and enabling technologies identified as high priority research areas by CV PFS stakeholders.

1.1   BACKGROUND

As government and industry move to embrace connected and automated vehicle (CAV) technologies, next-generation research will require more fully integrating transportation systems management and operations (TSMO) with CAV technologies to further improve safety, mobility, and the environment. Research must work to advance an understanding of how connected vehicle (CV) technologies interface with all transportation network infrastructure and how to best plan for the introduction of automated vehicles (AV) within this environment.

To accomplish this goal, the CV PFS began to develop a research plan (Task 5) and a concept of operations (Task 6) for the emerging area of CTCS. This effort included gathering input from a diverse set of stakeholders at an all-day workshop on April 30, 2019, in Ann Arbor, Michigan. During the workshop, the project team structured the discussion around the six CTCS use cases identified earlier in the project. Although these use cases helped guide the discussion, it became clear that the stakeholders wished to focus the CTCS research priorities on more specific research areas that could be described in more detail than the original six use cases. What resulted was a list of 14 high-priority research areas for CTCS grouped by use case and ranked by stakeholder priority. After the workshop, the project team and the PFS jointly decided to focus Task 5 on the top 10 research areas that came out of the stakeholder workshop. Next, the Task 4 report assessed each of the top 10 research areas in terms of technology and deployment readiness and extent of previous research and deployment efforts. Section 2, *Summary of Research to Date and Technology Readiness*, summarizes the CTCS use cases and the top 10 research areas.

1.2   SCOPE AND METHODOLOGY

The CTCS research plan is based on the findings from the stakeholder workshop, the Task 4 report, and experience and insights from the project team. Building on previous project tasks, the research plan drills down into greater detail by identifying gaps in existing research and defining a path from concept to deployment for each of the 10 prioritized research areas. A research roadmap identifies a set of near- and mid-term research projects and activities across a 5-year path from research to deployment. Research activities that were selected focus on early opportunities to incrementally deploy newly developed technologies and applications. The projects and their timing are based on consideration of key decision factors such as technology readiness, feasibility, deployment interest, and development effort. For each priority area, the research plan describes these factors and research needed to advance the area towards deployment in 5 years. The research plan also identifies longer term research activities (those beyond 5 years) at a higher level of detail for the CTCS areas where additional research may be needed beyond the 5-year roadmap.

1.3   DOCUMENT ORGANIZATION

This document is organized into the following sections:

- Section 2 summarizes work done on previous project tasks, including relevant research and deployment efforts to date, and provides an overview of the technology readiness levels for the prioritized research areas.

- Section 3 contains a discussion of related research roadmaps and presents a roadmap that summarizes the research proposed for the CTCS program area across a 5-year timeline.

- Section 4 specifies research activities proposed for each of the 10 priority research areas, grouping them as near- (0-2 years), mid- (3-5 years) or long- (6-10 years) term projects.

- Section 5 presents conclusions and next steps.

- Section 6 provides a comprehensive list of references used for this and other reports associated with this project.

2 SUMMARY OF RESEARCH TO DATE AND TECHNOLOGY READINESS

As explained in Section 1, the Task 4 CTCS Report contains an assessment of technology readiness levels (TRLs) for the priority research areas identified at the stakeholder workshop. In addition, that report also describes some key recent research and development (R&D) efforts for each of the top 10 research areas. Table 2-1 lists the top 10 research areas and their priority rankings grouped by the use cases identified earlier in this project. Use cases are listed from highest to lowest priority based on the highest-ranking research area in each use case. The rest of this section summarizes the Task 4 report including the TRL assessment and current and ongoing R&D efforts.

Table 2-1: Prioritized Research Areas by Use Case

Use Case	Research Area	Stakeholder Ranking
Arterial/Surface Streets	Queue Length Detection	1
	Virtual Detection	5
Connectivity and Early Automation	MAP File Creation	2
	Real-time Signal Optimization for Groups	4
	Position Correction	8
Multimodal	Pedestrian and Bicycle Safety*	3
Railroad Crossing Violation Warning	Imminent Safety	6
Connected Vehicle ICM	Data Sharing	7
Lane Management	Lane-level Dynamic Mapping	9
	Lane Availability	10

*Note: Although pedestrian and bike safety were captured as separate research areas in the workshop, they are combined in this report for a more holistic approach to intersection safety.

2.1 OVERVIEW OF TECHNOLOGY READINESS FOR PRIORITY RESEARCH AREAS

TRL assessments are a method of expressing the current maturity level of a technology on a scale from 1 to 9, with 9 being the most mature technology. This process helps to establish a clear understanding of current R&D efforts and gaps and identify the most worthwhile path for future research. Table 2-2 defines the nine TRL levels roughly grouped into four categories: basic research, applied research, development, and implementation.

Table 2-2: Definition of Technology Readiness Levels

	TRL	Definition
Basic Research	1	Basic principles and research
	2	Application formulated
	3	Proof of concept
Applied Research	4	Components validated in laboratory environment
	5	Integrated components demonstrated in a laboratory environment
Development	6	Prototype demonstrated in a relevant environment
	7	Prototype demonstrated in an operational environment
	8	Technology proven in operational environment
Implementation	9	Technology refined and adopted

The Task 4 report performed an initial assessment of technology readiness for each prioritized research area and assigned a TRL to each based on research and deployment completed to date and remaining gaps. Table 2-3 summarizes the TRLs assigned to each high priority research area along with a brief rationale for the assignment. The research areas are ordered from highest to lowest TRL. More details on the TRL assessments are contained in the Task 4 report.

Table 2-3: Technology Readiness Levels of CTCS Research Areas

Research Area	TRL	Rationale
MAP File Creation	8	Existing tools and procedures to create MAP files are consistent across independent entities. However, many improvements could be made, especially in the area of MAP validation.
Pedestrian and Bicycle Safety	6	Pilot deployments of pedestrian safety applications using CV technology are deployed in a limited number of places. However, the effectiveness of these applications is unproven.
Data Sharing	6	A limited number of operational deployments in the country show some success. Policy barriers continue to exist, as do data privacy concerns, particularly as these systems start to include CV data.
Queue Length Detection	5	Research on the use of CVs to determine queue length estimates for freeway applications that could be applied to similar applications on ramps and arterials is extensive.

Research Area	TRL	Rationale
		Ramp and arterial queue length estimation has been researched to a lesser extent.
Imminent Safety at Rail Crossings	5	Rail crossing safety technology has been demonstrated but it has typically not included CV technology.
Position Correction	5	Some research has demonstrated the ability to do correct positioning with existing systems such as smartphones and CV onboard units. However, the level of position correction and position accuracy required are still unknown.
Lane-Level Dynamic Mapping	4	Lane-level dynamic mapping has been demonstrated in a laboratory but there is not a high enough market penetration of CV for real world demonstration.
Lane Availability	4	Methods such as dynamic message signs have been fully proven in operational environments, but the CV component has not developed fully.
Real-Time Signal Optimization for Groups	3	A proof of concept has been demonstrated to optimize signal timing for individual vehicles, as well as for an intersection as a whole. However, limited R&D has been done for groups of vehicles.
Virtual Detection	3	The benefits of this technology have been simulated, and the concept is feasible given high enough market levels of penetration. However, prototyped technologies have not yet been widely developed or deployed.

2.2   OVERVIEW OF PREVIOUS AND ONGOING RESEARCH

The Task 4 report provides further details on previous and ongoing research or deployment efforts for each high priority research area. These research efforts provide a solid foundation for the research proposed later in this report. The following section summarizes the research presented in the Task 4 report at a very high level following the order of stakeholder priorities listed in Table 2-1.

2.2.1   QUEUE LENGTH DETECTION

Queue length detection and estimation, using CV and other technologies, has been extensively explored and researched. However, most research has focused on freeway applications, rather than on arterials and ramps. Relevant research efforts are as follows:

1. *Connected Vehicle as a Mobile Sensor for Real Time Queue Length at Signalized Intersections*, Changsha University of Science & Technology (China), 2019.
2. *Real-Time Queue Length Estimation for Congested Signalized Intersections*, University of Minnesota Twin Cities, 2009.
3. *USDOT Connected Vehicle Pilot Deployment: Tampa,* USDOT, 2019.

4. *Queue Spillback Detection and Control Strategies based on Connected Vehicle Technology in a Congested Network,* California PATH, 2014.

2.2.2   MAP FILE CREATION

USDOT created a tool that is currently used by various agencies for signal phase and timing (SPaT) and MAP file creation. The tool is based on the SAE J2735 standard for SPaT and MAP. Instructions for the tool are available, and were distributed widely, especially for agencies participating in the SPaT challenge. Although this existing tool is useful to many stakeholders, there are suggestions to improve it, and research is needed on how such improvements could be made and integrated into existing and/or new standardized tools. Relevant research efforts in this area are as follows:

1. *Basic Infrastructure Message Development and Standards Support for Connected Vehicles Applications,* Connected Vehicle Pooled Fund Study, 2018.
2. *Standardisation of SPaT and MAP,* SWARCO, 2014.

2.2.3   PEDESTRIAN SAFETY

Pedestrian safety, although widely understood as a vital requirement for shared public roadways, has not yet been fully resolved for CV. Limited deployments of pedestrian safety applications at intersections, primarily using smartphones, exist although challenges remain. For example, pedestrian infrastructure must be better defined in MAP and other file formats. Relevant research efforts are as follows:

1. *Accessible Transportation Technologies Research Initiative (ATTRI): State of the Practice Scan,* Carnegie Mellon University, 2017.
2. *Discussion Guide for Automated and Connected Vehicles, Pedestrians, and Bicyclists,* Pedestrian and Bicycle Information Center, 2017.
3. *USDOT Connected Vehicle Pilot Deployment: New York City,* NYC DOT, 2019.
4. *SmartCross,* Savari, 2016-2019.
5. *Smart Walk Assistant,* University of Arizona, 2018.

2.2.4   REAL-TIME SIGNAL OPTIMIZATION FOR GROUPS

Long-term research must identify the impact of changing signal timing schemes for groups of CAVs and the safety and mobility of that group of vehicles and other vehicles and roadway users. Some university studies have looked at the problem, and USDOT developed a prototype application called GlidePath. It provides automated longitudinal control through intersections but focuses on a single vehicle and does not adjust signal timing. Relevant research efforts in this area are as follows:

1. *Intersection Management via Vehicle Connectivity: The Intersection Cooperative Adaptive Cruise Control System Concept,* Virginia Polytechnic Institute and State University, 2014.
2. *Advanced Traffic Signal Control Algorithms, Appendix A: Exploratory Advanced Research Project: BMW Final Report,* University of California, Berkeley, 2013.
3. *GlidePath Prototype Application,* USDOT Application, 2015.

2.2.5   VIRTUAL DETECTION

One solution to overcome the lack of market penetration of CVs is to virtually detect vehicles that are not equipped with CV technology without actually using CV technology. There are various methods of detecting non-equipped vehicles, some that are infrastructure-based and others that are vehicle-based (essentially equipped AVs sharing information about other vehicles). The benefits of this approach have been simulated, but prototyped technologies have not yet been widely developed or deployed. Relevant research efforts are as follows:

1. *Virtual Detection at Intersections using Connected Vehicle Trajectory Data,* Purdue University, 2016.

2.2.6   IMMINENT SAFETY AT RAIL CROSSINGS

While safety at highway-rail grade crossings is a major issue in the United States, USDOT's Federal Railroad Administration has expressed interest in exploring CV applications to solve the problem. There have been a limited number of applications deployed at rail crossings throughout North America but none of them involve CV technology. Also, coordination with private railroads companies has been identified as an institutional issue. Relevant research efforts are as follows:

1. *TRAINFO,* TRAINFO, 2019.
2. *USDOT Connected Vehicle Safety for Rail,* USDOT, 2019.
3. *2017 Grade Crossing Research Needs Workshop,* Federal Railroad Administration, 2017.

2.2.7   DATA SHARING

Data sharing between different public agencies as well as private partners is an important element of any successful CAV deployment. It is both a technology issue and an institutional issue. There have been many examples of large-scale data sharing platforms deployed throughout the United States but so far none have included CV data and institutional issues such as privacy remains. Relevant research efforts are as follows:

1. *Regional Integrated Transportation Information System (RITIS),* RITIS, 2019.
2. *I-210 Connected Corridors,* Caltrans, 2019.
3. *Transcom,* Transcom, 2019.

2.2.8   POSITION CORRECTION

As AV technologies continue to be developed, questions on how precise the positioning must be remain. Some research demonstrates position corrections using existing equipment such as smartphones and CV on-board units. Additional research is needed on this topic, as well as on precision of the current technology and whether multiple data sources could be combined to provide a higher level of confidence. Relevant research efforts are as follows:

1. *Connected Vehicle Pilot Positioning and Timing Report: Summary of Positioning and Timing Approaches in CV Pilot Sites,* USDOT, 2018.
2. *Evaluation of Vehicle Positioning Accuracy by Using GPS-Enabled Smartphones,* University of Alberta (Canada), 2014.

2.2.9   LANE-LEVEL DYNAMIC MAPPING

Research is needed on how MAP files could be changed dynamically in response to roadway condition changes. Such research could support CV work zone applications and other CV applications during adverse weather such as when snow changes lane alignments. Some prototypes of lane-level dynamic mapping have been tested in a laboratory environment but not in a live environment. Relevant research efforts are as follows:

1. *Dynamic Map Update Protocol for Highly Automated Driving Vehicles,* Technical University of Darmstadt (Germany), 2017.
2. *Dynamic Map Update Using Connected Vehicle Data,* Mcity, 2016.

2.2.10 LANE AVAILABILITY

Lane availability, which identifies whether or not a signalized lane is accessible due to congestion, traffic incidents, or work zones, has traditionally used ITS infrastructure such as dynamic message signs. Some research has been done on how to apply CV technology but nothing has been developed or tested in an operational environment. Relevant research efforts are as follows:

1. *Human Factors for Connected Vehicles Transit Bus Research,* USDOT, 2019.
2. *Effects of Connected and Autonomous Vehicles on Contraflow Operations for Emergency Evacuation: A Microsimulation Study,* University of Central Florida, 2018.

3 RESEARCH ROADMAP

This section introduces the concept of a research roadmap and presents a CTCS research roadmap for the CV PFS and FHWA to help guide their future research activities. Research roadmaps come in many forms, some as simple as a list of proposed research projects organized by various research tracks and others illustrating research activities across a set timeline and different research tracks showing interdependencies among projects. The PFS roadmap is closer to the latter because it shows a graphic of proposed CTCS research with a 5-year timeline of projects for each prioritized research topic area to advance from current TRL to deployment (or near deployment). It also shows the key interdependencies among projects within each use case. Longer term projects (6 to 10 years out) and interdependencies that cross between use cases are not shown on the roadmap, but they are described in Section 4.

3.1 RELATED ROADMAPS

As explained above, many organizations use many forms of research roadmaps to help guide future research. USDOT used several research roadmaps within its CV program that have mostly run their course. In particular, the dynamic mobility applications (DMA) research plan[1] and its corresponding roadmap are relevant to PFS because some of its projects (e.g., MMITSS) were carried out by PFS. The DMA roadmap culminated with the current CV deployment pilots so it is no longer active; however, the results of the CV pilots will help inform future CTCS research. USDOT maintains other research roadmaps that might be relevant to CTCS such as FHWA's connected automation roadmap. Because these roadmaps are not always publicly available, the PFS will have to rely on their FHWA liaison to monitor them and coordinate with the PFS so as to maximize synergies, enable coordination or potential collaboration, and avoid undesirable duplication of efforts.

National research bodies, some states, and even other countries, have developed CAV research roadmaps. It is beyond the scope of this project to investigate every related roadmap that might have synergies with CTCS; however, the project team feels that the National Cooperative Highway Research Program's (NCHRP) CAV research roadmap is worth deeper investigation because of its close connection to the American Association of State Highway and Transportation Officials (AASHTO) and PFS. The initial 2015 version and the update of the NCHRP CAV research roadmap are discussed below.

3.1.1 NCHRP'S 2015 CAV RESEARCH ROADMAP

In 2014, in cooperation with AASHTO, NCHRP initiated the program 20-102 to assess the impacts of CVs and AVs on state and local transportation agencies. To help the NCHRP 20-102 program facilitate research in these topic areas, a draft research roadmap[2] was developed in 2015 as part of the previous NCHRP 20-24(98) project that identified a list of projects under four general clusters: institutional and policy, infrastructure design and operations, planning, and modal applications. Since then, NCHRP initiated several projects and task orders to cover some of the topics identified on the roadmap.

Of the topics identified in the 2015 NCHRP roadmap, only these three had clear overlap with the CTCS research areas:

- Relationships of connected and automated vehicle systems (project 2.4),

- Traffic control strategies with consideration of AVs (project 2.5) and

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[1] https://www.its.dot.gov/research_archives/dma/dma_plan.htm

[2] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-24(98)_RoadmapTopics_Final.pdf

- Data management strategies for CV/AV applications (project 2.10).

Of these, only the data management project has been programmed as a project (NCHRP 20-102[14]). Although this program has not yet begun, since it overlaps with the CTCS ICM data sharing area, its progress should be monitored, and it is identified in the CTCS research roadmap (see section 3.2). The other two projects (2.4 and 2.5) have not been programmed by NCHRP, and they do not appear to be moving forward so they cannot be identified on the CTCS roadmap.

3.1.2 UPDATE TO NCHRP'S 2015 ROADMAP

Recognizing the fast-moving nature of CAV, NCHRP started project 20-102(19) in March 2018 to update the 2015 roadmap and focus on priority research areas. This project is now in the second of two years. Its first task, which has been completed, was to provide commentary on the 2015 research roadmap.[3] Its second task is to provide an annual catalog of research topics in 2018 and 2019. The Year-1 catalog of research topics has been published and is available online[4].

The initial Year-1 research topics consisted of over 60 different topics under five major categories of research: Institutional and policy, transportation planning, infrastructure design and operations, IT infrastructure and data, and modal applications. Of these, several topics from the infrastructure design and operations category seemed relevant to the CTCS area, including "traffic management strategies with consideration of AV" and "infrastructure enablers for connected and automated vehicles and shared mobility."

Next, NCHRP prioritized the list of 60 topics into a list of 11 topics considered for funding in the fall of 2018. As of now, the one project that has been funded that is of greatest interest to PFS is NCHRP 20-102(24): "infrastructure enablers for connected and automated vehicles and shared mobility." Although this project is probably broader in scope than any of the CTCS research areas, it does consider how CAVs will interact with physical and digital infrastructure in ways that impact their standards and practices. As such, this project should be monitored as it moves forward.

3.2 CTCS ROADMAP

Figure 3-1 shows the CTCS research roadmap organized by the six use cases and the 10 priority research areas selected by the CTCS stakeholders. The number in parentheses next to each research area indicates the CTCS stakeholder priority. The TRL for each research area is indicated at the beginning and end of the timeline showing how far the research area is expected to advance in terms of readiness. The timeline is shown in the top row and extends for 5 years starting in January 2020 and ending in January 2025 (note that some activities start earlier than 2020 and some extend later into 2025). Because the CAV industry is fast moving, the project team felt that showing research at this level of detail beyond 5 years would be premature. Also, USDOT typically follows 5-year roadmaps for its research programs, and the CTCS roadmap is consistent with that approach. Section 4, *Research Activities*, provides long-term research ideas.

Each box in Figure 3-1 represents a high-level research activity and its duration, and each diamond indicates a milestone. Research activities (or projects) include a combination of white papers/studies, design efforts, prototype developments, or field tests as indicated by color. Depending on research area, some are better suited for a traditional R&D approach that involves exploratory white papers or studies followed by design, prototypes, and field tests. However, some areas, especially the enabling technology areas, are better suited for tool development and prototypes without a design element or field test. The interdependencies between the different research activities within the same use case are shown with arrows connecting the boxes. Interdependencies between activities that cross over different use cases are not shown in the figure but are discussed in Section 4.

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[3] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102(19)_Task1.pdf
[4] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102(19)_ResearchCatalog2018.pdf

The top row on the left in Figure 3-1 shows the major national CAV research programs discussed in Section 3.1. USDOT's most relevant research activities include the CV pilots and FHWA's connected automation roadmap. The primary USDOT CV research activity right now is the CV deployment pilot program which includes pilots in New York, Tampa, and Wyoming. The CV pilots are expected to wrap up in late 2020. These pilots will culminate in a benefits assessment and lessons learned, which will also lead to deployment tools, standards, and other tech transfer activities. Similarly, the FHWA Connected Automation roadmap will also lead to tools, prototypes and standards that could be useful resources to the CTCS program (e.g., the CARMA platform). The NCHRP 20-102 program and its CAV roadmap are also shown, and the outputs from these projects will also feed into tools, standards, and tech transfer. Finally, all these national activities will inform the entire CTCS research program as indicated by the wider down arrows.

The rest of the roadmap shows the proposed research in the CTCS uses cases and prioritized research areas (number in parentheses indicates priority ranking). Use cases and research areas are listed in the same order as Table 2-1, from highest to lowest priority. For each area, we show several research activities (boxes) and milestones (diamonds) and the key interdependencies. Section 4 describes the research activities and their justification in greater detail. The CTCS roadmap is presented here to provide the reader with an opportunity to see all proposed near- and medium-term research in one place. Long-term research activities are discussed in Section 4.

National CAV Research Programs

Timeline: 2020 | 2021 | 2022 | 2023 | 2024 | 2025

- USDOT CV Program — CV Pilots → ◇ Benefits Estimates and Lessons Learned
- FHWA Connected Automation R&D — FHWA Tools/Standards/Tech Transfer
- NCHRP 20-102 Program — CAV Roadmap Updates

Arterial/Surface Streets

- Queue Length Detection (1) — TRL 5 → Queue estimation through data fusion → Queue Estimation in Complex Environments; Queue estimation w/ spillbacks → TRL 8
- Virtual Detection (5) — TRL 3 → Conditions for virtual detection → Develop sensor fusion platform → CARMA Prototype → TRL 6

Connectivity and Early Automation

- MAP File Creation (2) — TRL 8 → Develop MAP guidance → Expand MAP creation tool → Prototype map validation tool → ◇ MAP file process mature → TRL 9
- Real-time signal opt. for groups (4) — TRL 3 → V2I coordination for groups → Multimodal V2I field test w/ groups → TRL 6
- Position Correction (8) — TRL 5 → Survey of positioning tech → Prototype VRS network → RTCMs to improve localization → TRL 7

Multimodal

- Pedestrian/Bike Safety (3) — TRL 6 → Simulation tool for X2I Intersections → Deployment of Connected Intersection with X2I → TRL 8

Railroad Crossing Violation Warning

- Imminent Safety (6) — TRL 5 → Deployment of Connected Intersection w/ rail crossing → TRL 7

Connected Vehicle ICM

- Data Sharing (7) — TRL 6 → NCHRP 20-102(14) → Survey of data exchanges with CV → Develop MAP repository → TRL 8

Lane Management

- Lane Level Dynamic Mapping (9) — TRL 4 → Improve BIM/RSM standards → Web tool for dynamic mapping → TRL 6
- Lane Availability (10) — TRL 4 → V2X for dynamic lane control; V2X for speed harm and traffic control → TRL 5

Key

- milestone ◇
- White paper/study
- Design/simulation
- Tool/Prototype
- Field test

Note: V2I = vehicle-to-infrastructure, V2X = vehicle-to-everything, X2I = everything-to-infrastructure

Figure 3-1: CTCS Research Roadmap

4 RESEARCH ACTIVITIES

This section provides the detailed descriptions of the research activities and projects that are shown on the CTCS research roadmap in Section 3, organized by use case and prioritized research area. It is ordered from highest to lowest priority based on the highest priority research area in each use case. The use cases are summarized at the beginning of each subsection and then the research topics within that use case are described in enough detail to enable a basic understanding of needs, high-level expected benefits and costs, and expectations for realization of CTCS research and development.

The research topics areas are broken down into three parts: the background discussing the state of the art; the research needed to address the important research gaps; and the proposed research activities that suggest how these gaps should be addressed. The background part mentions the stakeholder priority and the beginning TRL.

The recommended research activities are grouped as near-, mid-, and long-term activities. The short and mid-term activities are essentially research projects that trace back to the boxes shown in Figure 3-1. For each project, we provide the following information: description, deliverables, dependencies, duration and budget. The long-term activities describe suggested research that extends beyond the research roadmap's five-year time horizon. Since it is more far reaching. it is described at a higher level.

4.1 ARTERIAL AND SURFACE STREETS WITH TRAFFIC CONTROL AND RAMP METERING

This use case explores how connectivity will allow vehicles to interact with ITS technology beyond individual traffic signal controllers (such as ramp meters and adaptive signal systems) to better coordinate between these devices to improve the flow of vehicles as they move along corridors that may or may not connect with limited access roadways.

The priority research areas within this use case are queue length estimation and virtual detection.

4.1.1 QUEUE LENGTH DETECTION

BACKGROUND

A proper detection or a correct estimation of a vehicle queue length at an urban intersection or a freeway on-ramp is an important component of both effective traffic management and efficient operation of individual vehicles. Knowledge of queue lengths is needed to pinpoint intersection bottlenecks and determine their cause – excessive demand or poor traffic control. Information about vehicle queues is necessary for signal control (to minimize cycle failures and traffic spillbacks to upstream intersections) and for ramp metering (to minimize traffic spillbacks into arterials or other freeways). For individual vehicles, accurate queue information enables optimization of energy consumption. Queue length estimation was ranked highest priority in the CTCS stakeholder workshop conducted under Task 4.

A significant amount of research has been devoted to queue length estimation and queue spillback detection. Vehicle-to-everything (V2X) communications is a widely considered technology for application to queue estimation. The TRL for this technology is at the level of lab demonstration (TRL 5), and there is a need for a working prototype in the complex operational domain.

Vehicle queue estimation can be difficult, especially in the congested environment when traffic spillbacks occur. Challenges arise from traffic spillbacks to upstream junctions, when it becomes unclear where one queue ends and the other begins. There are also challenges resulting from the insufficient number of CVs and from multiple queues forming on a single approach; e.g., when part of the traffic is queued up to make a left turn, and the other part of

the traffic waits for a straight movement. Finally, queue estimation is made difficult from errors in vehicle localization.

RESEARCH NEEDED

The following three research issues must be addressed to advance V2X for queue estimation at intersections and interchanges to the next readiness levels.

1. Current research indicates that the accuracy and consistency of queue estimation via V2X largely depends on the penetration rate of CVs. Although the existing algorithms show effectiveness at a penetration rate of 25% and above, it is not possible to count on the immediate presence of so many CVs on the streets. Therefore, there is a strong need for techniques that would combine CV data with other data from alternative sources, such as: virtual detection devices (discussed in Section 4.1.2), Bluetooth or Wi-Fi readers located near intersections; in-pavement detectors measuring volume, occupancy, and speed; intersection cameras measuring traffic density and speed; and/or third-party probe data. It is important to show:

   ● how V2X data will be fused with the other measurements in real time;

   ● the measure of accuracy added by V2X to the queue estimation using only one or more alternative sources; and

   ● how and to what extent V2X with its growing penetration rate will replace other data sources for queue estimation.

2. The most interesting experiment with V2X for queue estimation would be at a complex intersection whose approaches have left- and/or right-turn pockets that are prone to spillbacks. An approach with a turn pocket may have more than one queue. For example, a left-turn and a straight movement are controlled by different signal phases, but the left-turn pocket is too short and the left-turning vehicles spill back adding to the straight-movement queue. Adding to the problem is the inaccurate localization of a CV, specifically, its lane. This part of the research is related to the precision of the MAP specification (see Section 4.2.1) and the accuracy of self-identification on the MAP (see Section 4.2.3). It is important to show:

   ● how V2X for queue estimation performs in the complex operational environment with turn pockets that have spillbacks;

   ● the possibility of correct identification and estimation of multiple queues on the same approach; and

   ● how other measurement data sources used for the queue estimation can be utilized for the vehicle MAP position correction.

3. Another difficulty of estimating vehicle queue arises when the queue spills back to the upstream junction. At this point, CVs at the tail of the queue may be too far from the intersection or metering light that generated this queue to be able to communicate with it. Instead, these vehicles may be connected to the upstream junction. Therefore, an approach to applying V2X to long queue estimation is required. Solutions may include connected infrastructure used for information coordination, or an ad-hoc sensor network, where CVs are sensors, used to deliver the information to the connected infrastructure from CVs that are out of the communication range. It is important to show:

   ● how V2X can be used to estimate long queues and queues with spillbacks to upstream junctions; and

   ● how the proposed solution works in the operational environment.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (timeframe 1 to 2 years) research activity

1. *Real-time vehicle Queue estimation through data fusion.* Real-time vehicle queue estimation using a combination of V2X data and alternative measurements: System design and implementation.
   - *Short Description*: This project will identify and explore real-time data sources suitable for queue estimation. It will develop a methodology for combining the available V2X data with the information stream coming from those sources and assess the efficacy of such data fusion.
   - *Deliverables*: Methodology and software implementation of data fusion evaluated in a simulation environment.
   - *Dependencies*: none.
   - *Duration*: 18 months.
   - *Budget*: $300K.

Mid-term (timeframe 3 to 5 years) research activities

1. *Queue estimation in complex environments.* Using V2X for queue estimation in complex environments (such as turn pockets with spillbacks): A field experiment.
   - *Short Description*: This project will address queue estimation at intersections with complex geometry: when approaches have multiple lane groups - turning left, going straight, turning right. Specifically, intersection approaches must serve several queues including a different queue for each different movement. Two or more intersections with different challenging features should be selected to conduct a field test of queue estimation.
   - *Deliverables*: Methodology for queue estimation in the presence of multiple queues at an approach; simulation results for intersections with complex approaches; field deployment of the methodology and evaluation of its performance.
   - *Dependencies*: CTCS Project "Real-time vehicle queue estimation (this section); CTCS Project "Guidance on MAP creation" (Section 4.2.1)
   - *Duration*: 24 months.
   - *Budget*: $950K.

2. *Queue spillback detection.* Using V2X for long queue estimation with spillbacks: System design and a field experiment.
   - *Short Description*: This project will address a situation when CVs at the end of the queue may be too far from the intersection or metering light that generated this queue to be able to communicate with it. Instead, these vehicles may be connected to the upstream junction. The goal is to design a system that deals with such scenarios. Solutions may include connected infrastructure used for information coordination, or an ad-hoc sensor network, where CVs are treated as sensors, used to deliver the information to the connected infrastructure from CVs that are out of the communication range.
   - *Deliverables*: Reference system design that includes communication access points and handover mechanism; implementation of the long queue estimation in simulation; and field deployment of the proposed system with its performance evaluation.
   - *Dependencies*: CTCS Project "Real-time vehicle queue estimation (this section); CTCS Project "Guidance on MAP creation" (Section 4.2.1)
   - *Duration:* 24 months.
   - *Budget:* $1.3M.

Long-term (timeframe 6 to 10 years) research activities

With these three projects completed, the queue detection technology is expected to be mostly mature with its readiness level advancing from TRL 5 to TRL 8 — technology proven in operational environment. To take this technology further, to the level of adoption (TRL 9), would require operational deployment of this technology at congested intersections together with deployment of video monitoring that could provide the ground truth for assessment of the technology performance.

4.1.2 VIRTUAL DETECTION

BACKGROUND

It is expected that CAVs will coexist with unequipped vehicles in the long term. Advanced safety systems such as adaptive cruise control, automatic emergency braking, blind-spot detection and warning, lane departure warning and lane keeping, and backup cameras are available on the vast majority of new cars today. These safety features rely on vehicle onboard sensors to sense the vehicle's surrounding environment, detect potential threats, and avoid the threats by either warning the driver or taking automatic maneuvers. Today's vehicle systems already have the capability to detect the surrounding targets (both equipped or unequipped), and the information about the detected targets can be broadcasted in Basic Safety Message (BSM) Part II and shared with nearby equipped vehicles and road infrastructure. Despite the advances in vehicle systems, sensing and machine learning techniques on target detection and classification, today's CV deployments are focused on using and sharing BSM core data that only contains the state of the CV itself (e.g., vehicle location, speed, and heading) without populating the detected target information in BSM Part II.

Many transportation agencies have deployed infrastructure-based sensors (e.g., radar, camera, or integration of both) to enhance or replace the traditional loop detectors for traffic monitoring and traffic signal control. These infrastructure-based sensors also have the capability to apply machine learning techniques on target detection and classification for both equipped or unequipped road users.

Research that uses equipped vehicles and infrastructure-based sensors to detect unequipped vehicles is limited. Virtual detection of unequipped vehicles by equipped vehicle and infrastructure is assessed as a TRL 3 because prototyped technologies have not yet been widely developed or deployed. Virtual detection was ranked 5th in terms of priority in the CTCS stakeholder workshop conducted under Task 4.

RESEARCH NEEDED

CAVs that use a combination of onboard sensors, including LiDAR, radar, and cameras, to sense vehicles' surrounding environment are floating sensors for detecting the following:

- surrounding road users (both equipped and unequipped);

- traffic queue length and vehicle arrival rate on the opposite directions;

- traffic incidents, accidents, and queue length on the opposite direction as well as on its traveling direction; and

- pavement condition and lane striping quality.

Fusion of vehicle perception data and infrastructure-based virtual detection via vehicle to infrastructure (V2I) communications could overcome the issue of low penetration rate of equipped vehicles and enable infrastructure-vehicle cooperative traffic signal control. For example, virtual detection provides a better characterization of vehicle platoons or strings that are approaching a signalized intersection; the traffic signal control system not only adapts the signal timing to the prevailing traffic conditions but also advises the movements of selected equipped vehicles for improved safety and mobility, where:

- an equipped vehicle is advised to slow down and create a safety gap between vehicles behind and vehicles in front such that the vehicles behind will stop safely to an upcoming red signal;

- an equipped vehicle is advised to speed up within the posted speed limit to catch up its leading vehicles to pass the intersection in green; and

- an equipped vehicle is advised to slow down or stop to avoid a potential conflict with an unequipped vehicle that is detected to run a red light on the perpendicular direction. Note that the equipped vehicle

may have difficulties to detect the unequipped vehicle with onboard sensors due to the blockage of sensors' field-of-view and line-of-sight for vehicle-to-vehicle (V2V) communications.

Research to advance the TRL of virtual detection includes:

1. Identify use cases, data requirements, and data availability for detection of unequipped vehicles by equipped vehicle and/or infrastructure sensors and for infrastructure-vehicle cooperative traffic signal control;

2. Develop an infrastructure-based sensor fusion platform to combine vehicle-based and infrastructure-based virtual detection with V2I communications; and

3. Develop prototypes based on the CARMA platform to populate vehicle-based virtual detection information in BSM Part II and showcase the benefits of virtual detection.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (timeframe 1 to 2 years) research activities

1. *Conditions for Virtual Detection*. Identify use cases, data requirements, and data availability for virtual detection.
   - *Short Description*: This project will conduct a survey and literature review on data sources available from the perception system in the research and commercial vehicles and from infrastructure-based traffic detection sensors, identify use cases, and develop data requirements for the virtual detection concept. There are a variety of vehicle perception systems that utilize different sensors (e.g., cameras, radar and LiDAR sensors) and processing techniques. Some vehicle perception systems have the capability to detect multiple objects surrounding the vehicle as well as object classification information. This project will also make recommendations on whether there is a need to expand the BSM Part II definition, specifically, Supplemental Vehicle Extensions, to capture the full set of vehicle perception data.
   - *Deliverables*: A white paper summarizing the existing date type and its characteristics of vehicle perception data and infrastructure-based traffic sensing data, describing use cases and data requirements for virtual detection, and recommendations on expanding BSM Part II message definition.
   - *Dependencies*: None
   - *Duration:* 12 months
   - *Budget:* $150K

Mid-term (timeframe 3 to 5 years) research activities

1. *Virtual Detection Through Sensor Fusion.* Develop an infrastructure-based sensor fusion platform.
   - *Short Description*: This project will develop an infrastructure-based sensor fusion platform that combines V2I-based vehicle self-location data and perception data (e.g., BSMs), and infrastructure-based traffic sensing data to provide a more complete perception of traffic environment at signalized intersections. This project will address 1) how vehicle self-location data and perception data could improve the coverage of traffic detection (including both equipped and unequipped vehicles) at signalized intersections and 2) the reliability and accuracy of identifying the same object that is detected by multiple data sources to overcome double counting. Due to the low penetration rate of connected vehicles, this project can be conducted at a site that has infrastructure-based traffic sensing system in place to achieve better performance.
   - *Deliverables*: Sensor fusion platform implemented in software and a final project report documenting system design, data approach, fusion algorithms, and test results.
   - *Dependencies*: CTCS Project "Conditions for Virtual Detection" (this section).
   - *Duration:* 24 months
   - *Budget*: $500K

2. *CARMA Prototype of Virtual Detection.* Develop a prototype based on the CARMA platform with existing CARMA-enabled vehicles to populate vehicle-based virtual detection.
   - *Short Description*: This project will develop a prototype based on the CARMA platform to populate vehicle perception data in BSM Part II and to process perception data received from nearby connected vehicles or connected signalized intersections to detect a potential threat that was not able to detect by its own perception system due to the blockage of sensors' field-of-view and line-of-sight for V2V communications. Scenarios to demonstrate the benefits of cooperative perception will be defined and tested at either controlled environment or selected site.
   - *Deliverables*: Prototype implemented in software and a final project report documenting system design, designed scenarios for cooperative perception, and test results.
   - *Dependencies*: CTCS Project "Conditions for Virtual Detection" (this section); CTCS Project "Virtual Detection Through Sensor Fusion" (this section).
   - *Duration:* 18 months
   - *Budget:* $500K

Long-term (time frame 6 to 10 years) research activities

With these three projects completed, virtual detection is expected to advance from TRL 3 to TRL 6 – Prototype demonstrated in a relevant environment. To advance this area further, the fusion platform must be implemented and field tested at selected sites to evaluate system performance and assess the readiness for wide deployment. Traffic congestion and incident detection of the fusion system could be provided to traveler information and mobile navigation systems such as Google Maps to allow travelers to make informed travel decisions.

4.2 CONNECTIVITY AND EARLY AUTOMATION SUCH AS LEVEL 1 LONGITUDINAL CONTROL

This use case explores how connectivity and automated vehicle functions will allow roadway capacity expansion through longitudinal controls, such as shorter headways that can be obtained through vehicle platoons. This use case leverages V2V communications to enable vehicle platooning but also V2I communications to communicate the arrival of vehicle platoons to ITS field equipment—mainly traffic signal controllers. The use case also leverages level 1 automation to automatically control the speed of CVs through intersections based on SPaT data.

The priority research areas within this use case are MAP file creation, real-time signal optimization for groups, and position correction.

4.2.1 MAP FILE CREATION

BACKGROUND

Per SAE J2735 Standard (the latest version 2016-03),[5] the primary use of the MAP message is to convey lane-level geometry for intersections with lane types including motor vehicular lanes, pedestrian crosswalks, bike lanes, and parking lanes. When combined with other SAE J2735 message sets such as SPaT and BSM, the MAP message can be used to support Advanced Driver Assistance Systems (ADAS) that automate/adapt/enhance vehicle systems for safety and better driving as well as to support intelligent traffic signal systems such as MMITSS.

MAP creation and validation continue to be critical impediments to the deployment of CV applications. MAP file creation was ranked 2nd in terms of priority in the CTCS stakeholder workshop conducted under Task 4. USDOT has created a web-based tool for MAP creation.[6] The tool has been used by many stakeholders, and several

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[5] https://saemobilus.sae.org/content/j2735_201603
[6] https://webapp.connectedvcs.com/isd/

stakeholders have developed their own tools that use Google Earth or site survey data for MAP creation. USDOT and Crash Avoidance Metrics Partnership (CAMP) have developed visualization tools that overlay MAP, SPaT, and BSM on Google Maps Satellite View. MAP creation is assessed to be a TRL 8 because there are existing tools and procedures to create MAP files that are consistent across independent entities. MAP validation, however, would probably be assessed at a TRL 4 or 5 because, although the visualization tools are very useful for validating V2I communications and SAE J2735 message encoding and decoding, the tools still lack the ability to detect MAP errors, and they are not easily integrated with MAP creation tools to apply the corrections necessary to fix the errors.

RESEARCH NEEDED

The fundamental question for advancing MAP creation is the usability of SAE J2735 MAP messages to support ADAS and traffic signal control applications. A CAV can use various onboard sensors and mapping technologies such as HD Maps and LiDAR point cloud for identifying its position. Furthermore, a CAV can use SAE J2735 MAP to determine lane restrictions, allowed through movements, connecting lanes and their lane attributes, conflicts with other lanes, pedestrian crosswalks, bike lanes, and how to associate with the SPaT message. This last capability is needed to determine the state of the signal that controls its movement and the state of the signal that controls the movements on the conflicting lanes. For example, when pedestrian crosswalks are included in the MAP and pedestrian signals are included in the SPaT, a vehicle that is intended to make a turning movement at the stop-line is able to determine the conflicting pedestrian crosswalk based on the MAP and warn the driver when the pedestrian signal is active (Walking or Flashing Don't Walk). Traffic signal control applications can use lane-level traffic signal performance measures such as queue length, delay, turning ratio, and adjust signal timing to immediately adapt to traffic demand.

In the future, it is likely that the SAE J2735 MAP will coexist with rather than replace vehicle-resident mapping technologies (e.g., HD Maps). Enhanced MAP file creation could provide important additional features as follows:

Increased coverage area. Coverage of the entire geometry of connected intersections, including vehicle lanes, pedestrian crosswalks at stop-line and midblock, bike lanes, unsignalized intersections between signalized intersections, and connections between vehicle lanes;

Increased accuracy of MAP creation. Although various mapping technologies could be used, the maps that represent the same intersection must reference to the same ground truth - intersection lane markings. The existing MAP creation tools are based on satellite images (e.g., Bing Maps, Google Maps). Lane detection is a well-researched area of computer vision with applications in automated vehicles and driver support systems. Expanding the existing MAP creation tools to include image processing techniques that automatically extract lane markings from satellite images could significantly reduce the human labor and errors in the process of MAP creation and increase the accuracy and usability of the created SAE J2735 MAPs.

Increased flexibility for MAP developers/creators. Flexibility to add optional MAP data elements would support different ADAS and traffic signal control applications; for example, posted speed limit may not be required by the Red-Light Violation Warning application but would be required by the eco-driving application and traffic signal coordination application. This feature would also facilitate the ability to adjust portion lane geometry based on observed MAP errors.

Improved MAP validation tool. MAP validation requires more extensive effort than MAP creation as the errors in detecting the lane of travel could be due to MAP errors or GPS measurement errors, therefore, developing an automatic or semi-automatic MAP validation tool that can validate the MAP against the lane markings is necessary for the deployment of CV applications. The MAP validation tool, at the first stage, can be an offline version that records video and vehicle GPS traces and applies lane detection techniques on recorded data to validate the MAP and report MAP errors. Upon the proof of concept, the tool can be converted to an online version that detects lane marking and reports MAP errors in real-time. Also, providing a visualization overlay of recorded BSMs on top of the MAP lane geometry would help to pinpoint possible MAP errors.

When CAVs become more prevalent and sharing of vehicle sensing data becomes more common, MAP creation, validation, and update will rely on the massive amount of data generated by CAVs. The development of a MAP

validation tool that combines image processing techniques for lane detection and GPS for localization will greatly assist the infrastructure owners and operators (IOOs) as they continue to provide SAE J2735 MAP messages that are consistent with the advances in ADAS.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (timeframe within 2 years) research activities

1. *Guidance on MAP creation.* Develop a synthesis document to guide the IOOs on MAP creation and to ensure interoperability across different jurisdictions

   - *Short Description*: Several efforts are in progress to address the interoperability issues including the IOO/OEM Forum and SPaT Challenge. This project will cooperate and leverage the ongoing efforts to develop a synthesis from the IOOs' point of view with the real-world examples to guide how to create MAP for
        1) incorporating unsignalized intersections between signalized intersections;
        2) connection between though-only lanes and left-turn or right-turn lanes and between merging lanes at connected intersections; and
        3) expanding the intersection MAPs to freeway ramps and ramp meters.
   - *Deliverables*: A synthesis document summarizing guidance on MAP creation.
   - *Dependencies*: Ongoing IOO/OEM Forum efforts addressing interoperability across different jurisdictions.
   - *Duration*: 12 months
   - *Budget*: $150K

2. *Improve the MAP creation tool.* Extend the existing MAP creation tool to improve the coverage, flexibility, and accuracy of MAP creation.

   - *Short Description*: This project will expand the existing USDOT MAP creation tool to allow selection of satellite and arterial imagery (Bing Maps, Google Maps) and include automated lane marking extraction from satellite images and pre-populated lane geometry (lane center line and lane width) from the extracted lane markings. The tool must also be expanded to include pedestrian crosswalks at a minimum and with the option to include infrastructure features such as bike lanes.
   - *Deliverables*: Expanded MAP creation tool.
   - *Dependencies*: Existing USDOT MAP creation tool and CTCS Project "Guidance on MAP creation" (this section).
   - *Duration*: 18 months
   - *Budget*: $250K

Mid-term (timeframe 3 to 5 years) research activities

1. *Prototype MAP validation tool*. Develop a prototype MAP validation tool that incorporates lane detection as ground truth for MAP validation and error reporting.

   - *Short Description*: The accuracy of MAP file can only be measured with respect to the ground truth (i.e., lane markings). Vision-based lane detection is a well-researched area for ADAS and automated driving. Commercial off-the-shelf (COTS) vision systems with lane detection are widely available. This project will develop a prototype MAP validation tool, potentially based on the existing CAMP SPaT/MAP validation tool, to incorporate lane detection with either a portable COTS vision system such as Mobileye or an instrumented Connected Fleet vehicle to automatically detect and log map errors so that the errors can be corrected using the MAP creation tool.
   - *Deliverables*: A functional prototype MAP validation tool and user manual.
   - *Dependencies*: CAMP SPaT/MAP validation tool; CTCS Project "Improve the Map Creation Tool" (this section)

- *Duration*: 24 months
- *Budget*: $350K

Long-term (time frame 6 to 10 years) research activities

With the completion of the three projects above, MAP creation and MAP validation will be fairly mature and probably at a TRL 9. However, there are other research activities that could advance this area further as it gets deployed. For example, advances could be made in fusion of vehicle-based sensing data and satellite and arterial imagery for automated MAP corrections, updates, and creation. Images and other data gathered from a higher level AV can be processed to generate local lane geometry around the vehicle; data gathered from the AVs driving on the same roadway segment can be combined to create lane geometry MAP in real-time, to compare against the existing MAP files on error detection and MAP update as well as creating MAP files for locations where they do not exist.

4.2.2   REAL-TIME SIGNAL OPTIMIZATION FOR GROUPS

BACKGROUND

The MMITSS proof of concept has demonstrated the ability to optimize signal timing based on connected vehicle data. The MMITSS optimization objective can focus on minimizing the intersection delay, travel time, or queue length, maximizing the throughput, or a weighted combination of any of those. Traffic Optimization for Signalized Corridors (TOSCo) is a project led by the CAMP consortium that uses SPaT data, V2V communications and in-vehicle intelligence to allow CAVs to form vehicle strings and cooperate among each other to automatically control vehicle speed such that they can travel through a signalized corridor in the most efficient manner. The TOSCo vehicles can send the information regarding the formulation of cooperative vehicle strings to connected signalized intersections so that the intersections can adjust signal timing in real-time to maximize the throughput of TOSCo vehicles crossing the connected intersections. In addition, the TOSCo vehicles can coordinate with the other vehicles in their vehicle group (or vehicle string) and adjust vehicle speed based on the updated SPaT data to take advantage of signal timing adjustments. To effectively optimize an intersection crossing by a vehicle group, the intersection must have the ability to:

1. Communicate with CVs including cooperative vehicle groups such as TOSCo vehicles.

2. Inform agents approaching the intersection about current signal phase and its estimated remaining duration using the SPaT and MAP standards. Phases in actuated signals vary depending on presence and volume of vehicular and pedestrian traffic.

3. Inform agents (mainly vehicles) crossing the intersection about their expected arrival time and potential blind zones.

4. Inform agents about the detected activity in their blind zones: e.g., an equipped vehicle can be notified about an unequipped vehicle that they cannot see, but who may be crossing their path.

5. Accept give-me-green requests from the approaching agents (e.g., vehicle groups) and prioritize signal phasing appropriately.

6. Warn agents crossing the intersection about detected red light violations. To ensure safety, violators must have the right-of-way.

7. Incorporate level 1 automation by automatically braking the vehicle or controlling the speed of the vehicle through the intersection.

This area is considered a TRL 3. Real-time signal optimization for groups was ranked 4th in terms of priority in the CTCS stakeholder workshop.

RESEARCH NEEDED

To advance this research to the next level, the following problems must be solved:

1. Most signals do not have fixed cycles, because they use various actuation mechanisms to extend green phases or initiate an early green phase start. Accurate and robust prediction of the green phase duration would improve intersection throughput by motivating the agents who can cross the intersection in time to do so. It would also improve intersection safety by sending a timely warning to those who won't make it to slow down and stop. This could also be achieved through level 1 automation. The signal phase prediction could be facilitated by the historic time-of-day phase duration data, by real-time approach detector measurements or Bluetooth readings, or by give-me-green requests from approaching connected agents.

2. Coordination of vehicle-level and road-level control is an ongoing research issue. The vehicle level control system makes a group of CVs move in a fuel-efficient manner by reducing the number of stops at intersections. The flow through intersections is increased by automatically forming platoons or vehicle stings with minimal inter-vehicle spacing. The road link level control system includes signal timings that are tuned to increase traffic throughput. The goal is to improve the effective green (so that the green time is not wasted) and progression quality (so that most vehicles arrive at the intersection during green time). Combining an accurate signal phase prediction with an accurate vehicle queue estimation (see Section 4.1.1) would enable effective speed advisory or control for CVs approaching an intersection individually or in vehicle groups (e.g., platoons or vehicle strings) to optimize progression quality crossing a section of connected signals.

These objectives serve the goal of mobility improvement and must be achieved under constraints that ensure safety of vehicles with respect to other vehicles. The degree to which it is possible to tweak phase timing in the signal is a further constraint. The main control variables will be phase priorities. The goal is to propose, develop, and demonstrate an adaptive signal control system with multi-parametric optimization. This research would greatly benefit from building on the queue estimation described in Section 4.1.1.and the intersection MAP described in Section 4.2.1.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (timeframe within 2 years) research activities

1. *Vehicle-infrastructure (V2I) coordination for groups:* system design and simulation.

   - *Short Description*: This project will address the two research needs described above in a simulation environment. This project can leverage the existing MMITSS VISSIM simulation platform and outcomes of project "Queue estimation through data fusion" (Section 4.1.1) to improve the accuracy of phase remaining time precision, incorporate TOSCo vehicle group formulation and cooperative speed control strategies and coordination of vehicle-level and road-level control schemas into the simulation platform.
   - *Deliverables*: Simulation based study and documented test results.
   - *Dependencies*: CTCS Project "Queue estimation through data fusion" (Section 4.1.1).
   - *Duration*: 18 months
   - *Budget*: $300K

Mid-term (timeframe 3 to 5 years) research activities

1. *Multi-modal V2I field test for groups:* System design and operational field test.

   - *Short Description*: This project would transfer the outcomes of the project "Vehicle-infrastructure (V2I) coordination for groups: System design and simulation" to practice, namely, testing the technology in an operational environment.
   - *Deliverables*: Field deployment of V2I test for groups and a quantitative assessment of its performance.

- *Dependencies*: CTCS Project "V2I coordination for groups: system design and simulation" (this section) and CTCS Project "Queue estimation in complex environments" (Section 4.1.1).
- *Duration*: 30 months
- *Budget*: $1.5M

Long-term (timeframe 6–10 years) research activities

The completion of the two listed projects would advance signal optimization for groups from TRL 3 to TRL 6 – prototype demonstrated in a relevant environment. The next logical step is to test this technology in a group of intersections. The setting could be a major arterial with a sequence of intersections forming a multimodal corridor. Also, more highly automated CAVs could be included in the testing to test how well infrastructure can control the speed of vehicles (and groups) through intersections, thus advancing the signal optimization for groups to TRL 9.

4.2.3 POSITION CORRECTION

BACKGROUND

Lane-level vehicle positioning is important for traffic management. Traffic control at signalized intersections and at metering locations, and the freeway CV applications, such as variable speed limit, curve speed warning, queue warning, and reduced speed zone warning, are all at the lane-level. Field tests conducted at the California CV Test Bed revealed that using RTCM corrections can reliably achieve accurate lane-level vehicle positioning. Including RTCM corrections as one of the required broadcast messages at connected intersections can significantly improve the effectiveness of CV applications, on both the infrastructure and vehicle sides.

Position correction is assessed to be TRL 5 because the effectiveness of RTCM corrections has only been demonstrated using local base stations and was ranked 8th in terms of priority in the CTCS stakeholder workshop. Additional research could establish a state-wide and nationwide GNSS network to support RTCM broadcasts for position corrections. The emphasis of this research is not to develop vehicle positioning and localization technologies (which already are active research areas for automated driving) but rather to provide additional position correction data source to support and expedite the development of CAVs.

RESEARCH NEEDED

The effectiveness of RTCM corrections depends on the distance between a base station and the connected intersection (i.e., the RSU), and the reliability of real-time data streaming of RTCMv3 messages to the RSU. There are many base stations deployed nationwide for environmental monitoring. Although many of the base stations provide access for streaming RTCMv3 messages in real-time, the data streaming could be interrupted due to station maintenance and/or lack of support for continuing data streaming. The Virtual Reference Station (VRS) concept is a proven implementation of networked RTK. Observation data at the VRS are created from the data of surrounding base stations as though they had been observed on that position by a GPS receiver. Use cases of the VRS concept for RTCM broadcasts include:

- Use a VRS for the RSU which has no base stations within the desired distance – increasing the spatial coverage of RTK network; and

- Use a VRS for the RSU whose nearest base station is down – improving the reliability of real-time RTCMv3 data streaming.

Research to advance the TRL of this area includes:

1. Understand the characteristics of GNSS base stations in the nation, availability of RTCMv3 data streaming, protocols to access the data streaming, and policies to share the data;

2. Establish statewide and national-wide VRS network(s) to increase the spatial coverage and reliability of RTCM position corrections, where the system can

a. Automatically select the best base station or establish a VRS to stream RTCM corrections to a connected intersection;

b. Monitor the quality of the data streaming and establish a VRS in case the desired base station is down; and

c. Provide RTCMv3 data streaming over cellular to connected fleet vehicles so the vehicle will have position corrections both within or outside the communication range of an RSU.

3. Compared with vehicle positioning and localization techniques that use vehicle on-board sensors, the accuracy of locating vulnerable road users such as pedestrians and cyclists on roadways by using mobile sensors is less developed. Using RTCM corrections has the potential to improve the accuracy of pedestrian and cyclist detection thereby improving safety.

RECOMMENDED RESEARCH ACTIVITIES

<u>Short-term (timeframe within 2 years) research activities</u>

1. *Nation-wide survey of GNSS base stations.* Survey the availability of RTCMv3 data streaming, communication protocol, and data sharing policy.

   - *Short Description*: The National Oceanic and Atmospheric Administration's National Geodetic Survey (NGS) manages a national network of Continuously Operating Reference Station (CORS). The CORS network comprises over 1,880 RTK base stations that broadcast corrections, usually over the internet. Some States manage their own network of RTK base stations, for example, the California Real Time Network (CRTN) consists of over 580 RTK base stations. The characteristics of these base stations vary in terms of the type of real-time correction data streams (RTCMv2 vs RTCMv3), updating rate, communication protocol, data sharing policy, and operation mode (single base RTK vs network RTK). This project will conduct a survey on RTK base stations throughout the United States, determine the characteristics of these base stations, and assess the readiness of utilizing the existing RTK base stations for RTCM broadcasts at connected infrastructure which has the potential to provide a free solution to providing lane-level vehicle positioning for connected vehicles
   - *Deliverables*: A document summarizing the current status of national-wide RTK base stations and their data streaming characteristics and assessing the readiness of RTCM broadcasts at connected infrastructure.
   - *Dependencies*: None
   - *Duration*: 12 months
   - *Budget*: $100K

<u>Mid-term (timeframe 3 to 5 years) research activities</u>

1. *Prototype VRS network.* Develop a prototype VRS network that integrates with existing GNSS base stations and provides networked RTK solutions to connected intersections and freeways.

   - *Short Description*: Network-RTK provides corrections based on multiple base stations in the network. It overcomes the limitation of single base RTK which requires the connected vehicles are in the vicinity of an RTK base station. This project will employ and integrate VRS technology with existing networks of RTK base stations to provide network RTK corrections for RTCM broadcasts at connected infrastructure. Specifically, a computation center (or server) collects raw data from networks of RTK base stations, computes errors of a VRS at or near the location of connected infrastructure (e.g., RSU) based on carrier phase measurements from multiple RTK base stations, and sends corrections to the connected infrastructure to broadcast over-the-air to CVs.
   - *Deliverables*: VRS network implemented in software and a final project report documenting system design, data approach, and test results.
   - *Dependencies*: Project "Nation-wide survey of GNSS base stations".

- *Duration*: 18 months
- *Budget*: $200K

2. *RTCM for better localization.* Using RTCM corrections to improve localization of vulnerable road users.

- *Short Description*: Position accuracy and power consumption are the two major concerns on utilizing mobile-phone applications in a connected vehicle environment. The project will assess the improvement on the accuracy of mobile-phone positioning by utilizing RTCM corrections through field testing. Mobile-phone receiving RTCM corrections over the Cellular network and interfacing with an external RTK-enabled GPS receiver for the use of RTCM corrections will be developed. The success of this project could lead to COTS portable and self-powered device that is carried by vulnerable road users to broadcast their position with much improved accuracy that provides foundation to support CV safety applications for vulnerable road users.
- *Deliverables*: A document describing system design, implementation, and test results.
- *Dependencies*: CTCS Project "Nation-wide survey of GNSS base stations" (this section) and CTCS Project "Prototype VRS network" (this section).
- *Duration*: 24 months
- *Budget*: $400K

Long-term (time frame 6 to 10 years) research activities

With the completion of the three projects above, position correction would be advanced from TRL 5 to TRL 7 – Prototype demonstrated in operational environment. Longer term research should look at how CAVs will use a combination of data sources and technology for position correction, including 3D LiDAR point cloud, differential GPS, RTCM, computer vision, and machine learning among others, because no single positioning technology is enough for all driving environments. For example, RTCM position corrections are effective in open sky environment but not in urban canyon environment. With the continuous advancing in vehicle-based positioning technology and the emerging markets that provide position corrections as a service, other research activities that integrate vehicle-based positioning technology on the infrastructure side for low-cost deployment could advance this area further.

4.3 MULTI-MODAL ASPECTS INCLUDING TRANSIT, FREIGHT, PEDESTRIANS, BIKES

This use case explores how connectivity will allow transit and freight vehicles, as well as non-motorized modes, to interact with other vehicles, pedestrians, and roadway field devices to improve multimodal operations along a corridor(s). This use case represents a bundle of potential services.

The only priority research area within this use case is pedestrian and bike safety. Initially, the project team separated the pedestrian safety area from bike safety. However, the research on intersection safety treats pedestrian and bikes together. This is because one cannot discuss pedestrian safety without considering a danger presented to pedestrians by cyclists. Therefore, in this section we address pedestrian and bike safety together.

4.3.1 PEDESTRIAN AND BIKE SAFETY

BACKGROUND

Intersections are dangerous: nationwide, 40% of crashes, 50% of serious collisions, and 20% of fatalities occur in intersections. For example, the fatalities in the San Francisco Bay Area alone increased by 43% between 2010 and 2016 to reach 455 people, of which, in San Francisco, 62% were cyclists or pedestrians. Intersections are challenging because of complex interactions among pedestrians, bicycles, and vehicles; absence of lane markings to guide vehicles; combinations of signal phases that prevent determining who has the right of way; obstructions

from stopped vehicles; and illegal movements. Improving intersection safety is urgent. Pedestrian safety was ranked 3rd, and bike safety was ranked 12th in terms of priority in the CTCS stakeholder workshop.

Responding to the road safety crisis, cities have launched Vision Zero (VZ) plans, seeking to eliminate traffic injuries and deaths, through physical modification of the road infrastructure to reduce vehicle mobility and create a safe passage for cyclists. However, crashes happen because drivers, cyclists, and pedestrians face uncertainties that lead to wrong decisions and end in crashes. Spatial uncertainty occurs when an agent at an intersection is unable to detect other agents; temporal uncertainty occurs when the agent is unable to accurately predict its own and others' right of way. These challenges are not fully addressed by the "road diet" and road redesign prescribed in VZ plans.

A connected intersection equipped with sensors to remove spatial and temporal uncertainties does not require costly physical modification of road infrastructure as in VZ, but relies on four components: (1) sensing; (2) interpretation of sensor measurements; (3) anyone-to-infrastructure (X2I) connectivity, extending the concept of V2I connectivity; and (4) signal phase prioritization. The cost of these components ranges from $25K to $200K per intersection depending on the intersection size, number of approaches and exits, and number of lanes in those. This cost will come down in the future as a higher CV market penetration will reduce the need for infrastructure-based detection. Such a "connected" intersection is characterized by the six functional properties:

1. Communicate not just with CVs, but with all connected agents (vehicles, cyclists, pedestrians) crossing the intersection. Extending the concept of V2I, this is called anyone-to-infrastructure (X2I).
2. Inform agents approaching the intersection about current signal phase and its estimated remaining duration using the SPaT and MAP standards. Phases in actuated signals vary depending on presence and volume of vehicular and pedestrian traffic.
3. Inform agents (mainly vehicles) crossing the intersection about their potential blind zones.
4. Inform agents about the detected activity in their blind zones: e.g., a cyclist can be notified about a pedestrian that they cannot see, but who may be crossing their path.
5. Accept give-me-green requests from the approaching agents and prioritize signal phasing appropriately.
6. Warn agents crossing the intersection about detected red light violations. To ensure safety, violators must have the right-of-way.

It must be assumed that any agent (vehicle, cyclist, pedestrian) crossing the intersection may be connected or unconnected. It is also important to remember that at critical intersections that are parts of heavily used travel corridors, safety improvements must take into account mobile efficiency and should not result in jamming the traffic.

A good amount of research has been conducted to test this concept. The technology underwent several tests in a controlled setting, but not yet in the operational environment so it has been assessed as a TRL 6.

RESEARCH NEEDED

Addressing the following research issues will advance and promote X2I-based technologies for safety applications:

1. To make the most of the three approaches to safety improvement described above, we must know which one, or what combination of these, is most applicable at a given intersection or road network. Conversely, ask the question: which intersections of the given geographic area would benefit from X2I deployment the most? Intersections must be characterized on several levels:

   ● Intersection geometry that considers all admissible agent (vehicle, bicycle, pedestrian) maneuvers; conflict zones; and potential blind zones, which describe existing spatial uncertainties.

   ● Traffic volumes going through the intersection and potential intersection throughput, which helps to assess intersection mobility and safety performance.

   ● SPaT that determines if risky maneuvers (e.g., permissive left turn or right turn on red) are allowed, and if phase durations can be accurately predicted in case of actuated signals. The phase prediction accuracy translates to the measurable improvement of intersection throughput.

- Incident statistics showing what intersection characteristics correspond to a larger number of incidents and their severity.

This work is tightly connected with the MAP research area (see Section 4.2.1), particularly in parts where MAP defines bicycle and pedestrian movements.

The X2I effectiveness can be quantified in terms of mobility and safety performance measures by comparing "with X2I" and "without X2I" simulation scenarios. Mobility performance measures include intersection throughput, number of stops of individual vehicles during intersection crossing, and time of agents' intersection crossing. Safety performance measures include number of emergency stops (simulated collisions) and number of vehicles not properly yielding to pedestrians and cyclists.

2. A deployed connected intersection should have the six functional properties described above. The intersection intelligence has three components: sensing, interpretation of sensor measurements, and connectedness. Figure 4-1 shows a reference configuration instrumentation of the intersection enabling these components as an example of how an intersection could be instrumented. The need for infrastructure-based sensing likely will diminish, however, as the CV market penetration increases over time.
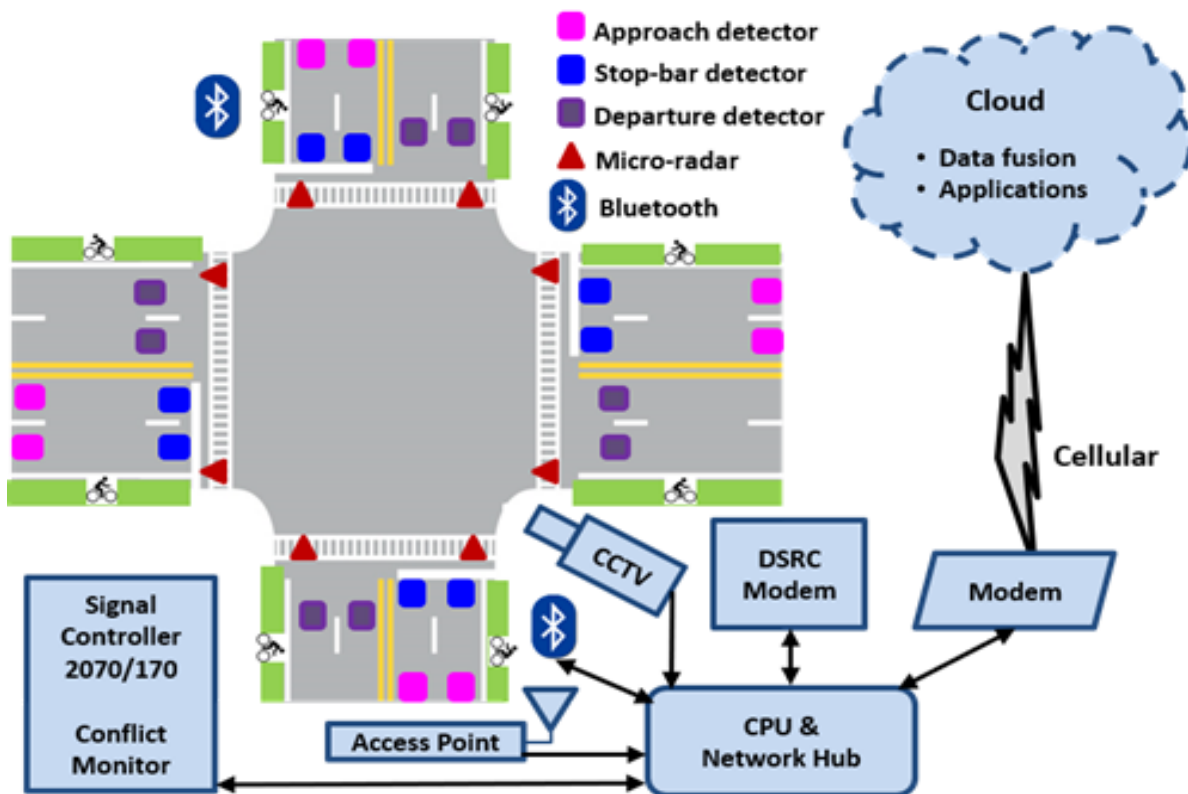

Figure 4-1: Reference Instrumentation of a Connected Intersection with Sensing

Prior to full deployment of CVs, the intersection must be equipped with approach, stop-bar, and departure sensors to detect vehicles; ped/bike sensors (e.g., micro-radars or cameras) to identify crossing pedestrians and cyclists; and optional CCTV cameras to enable video monitoring. All sensors transmit their data for processing to the CPU through an access point. Detection equipment enables functionality items 4, 5, and 6. The CPU is connected to the signal controller with a conflict monitoring card that prevents conflicting signal phases being activated together. This connection provides CPU with access to SPaT information as well as the ability to activate certain phase. Red light violations are identified by the CPU when it detects an agent performing a maneuver prohibited by current signal phase combination. The DSRC modem is used to broadcast the state of the intersection (SPaT + information

about presence of agents at specific lanes or crosswalks) and warnings about the detected red light violations to CVs. DSRC is the backbone of V2I. Emergency vehicles and transit can use DSRC to send give-me-green requests. The purpose of the Bluetooth connector is to extend V2I technology enabled by DSRC to X2I, informing connected agents other than vehicles about the state of intersection and red light violations as well as accepting give-me-green requests from those agents as they approach the intersection. These give-me-green requests are functionally similar to push-to-walk buttons that one encounters at some pedestrian crosswalks. Users will be able to issue give-me-green requests and get updates about the state of the intersection through a smartphone application. Data processed by CPU are uploaded to the cloud for long-term analysis and archiving via cellular link.

This reference instrumentation is modular: all or just some of the equipment can be installed by a transportation authority at a given intersection, depending on the available budget. Saving on equipment translates into reduction of intersection intelligence: e.g., intersection without detection cannot identify the presence of agents in specific lanes or crosswalks or issue warnings about red light violations, but it can still update SPaT and accept give-me-green requests and use them for phase prioritization. Also, the need for infrastructure-based detection will diminish once CV deployment is more widespread.

Research should include deploying the connected intersection in the operational environment. This research is synergistic and has the potential to overlap with the real-time signal optimization for groups (see Section 4.2.2).

RECOMMENDED RESEARCH ACTIVITIES

Short-term (timeframe 1 to 2 years) research activity

1. *Simulation tool for X2I intersections.* Develop a simulation-based tool for quantitative assessment on where to deploy X2I with a focus on which intersections need X2I to improve safety.

   - *Short Description*: This project will develop simulation-based tools for multi-level intersection characterization that takes into account intersection geometry, traffic volumes, signal configuration, possible agent maneuvers and incident statistics. The idea is to enable a city-scale analysis of intersections to pinpoint those that would benefit the most from X2I deployment. This project will also address the safety/efficiency tradeoffs at intersections. This is especially important for intersections in busy travel corridors.
   - *Deliverables*: Documented simulation-based software package for intersection analysis.
   - *Dependencies*: CTCS Project "Guidance on MAP creation" (Section 4.2.1).
   - *Duration*: 18 months.
   - *Budget*: $350K.

Mid-term (timeframe 3 to 5 years) research activity

1. *Deployment of connected intersection with X2I in operation.* Operational deployment of the connected intelligent intersection with sensing.

   - *Short Description*: The intersection intelligence has three components: sensing, interpretation of sensor measurements, and connectivity. Figure 4-1shows a reference configuration instrumentation of the intersection enabling these components as an example of how an intersection could be instrumented.
   - *Deliverables*: Field deployment of a connected intersection; and a methodology for a quantitative assessment of its performance.
   - *Dependencies*: CTCS Project "Guidance on MAP creation" (Section 4.2.1).
   - *Duration*: 30 months.
   - *Budget*: $1.5-2M.

Long-term (timeframe 6 to 10 years) research activities

The completion of the two listed projects would advance the application of connected infrastructure to pedestrian and bike safety from TRL 6 to TRL 8 – prototype demonstrated in operational environment. The next step would be

the assessment of X2I technology effectiveness by monitoring the usage activity by cyclists and pedestrians in combination with video monitoring. This step would advance the technology to adoption – TRL 9.

4.4 RAILROAD CROSSING VIOLATION WARNING

This use case explores how DSRC technology might be used to improve safety at grade-level rail crossings, particularly in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic. It is assumed that the rail crossings are at or next to signalized intersections.

The only prioritized research area within this use case is imminent safety at rail crossings.

4.4.1 IMMINENT SAFETY

BACKGROUND

Safety at highway-rail crossings is an issue that affects many different stakeholders in many different environments, from unsignalized crossings in rural locations to signalized crossings in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic.

In 2015, more than half of public at-grade crossings had automatic warning systems (flashing lights and/or gates) but very few private at-grade crossings did. Still, more than 60% of collisions occurred at crossings with automatic warning systems. A study on driver behavior using cameras installed in cars found that 46% of the time, drivers were likely engaged in secondary tasks and 35% of the time, drivers failed to look either left or right on approach to passive grade crossings. Safety at railroad crossings was ranked 6th in terms of priority in the CTCS stakeholder workshop.

In general, 94% of train-vehicle collisions could be attributed to driver behavior or poor judgement. An advanced warning system that provides another source of information to travelers, perhaps an in-vehicle notification to immediately and directly alert the driver, could help further improve safety. This could also be a valuable data source for AV systems.

Although rail intersection safety applications have been recently demonstrated in operation, they have rarely included CV technology. There are also limitations on the ability to expand existing systems because of the lack of data sharing agreements and other coordination with private railroad companies. Therefore, this area is assessed at TRL 5.

RESEARCH NEEDED

Due to the difficulty of coordinating with the railroad industry, it is unlikely that connected rail crossing safety applications will be based on direct vehicle-to-train communication. The most feasible solution would be to extend the connected intersection and X2I concept to include rail crossings. Thus, the communication between vehicles and trains would occur through connected infrastructure.

The research problems of connected safety applications for multi-modal intersections are discussed in Section 4.3.1. One effort that could advance this area closer to deployment is to deploy the connected intersection concept in an operational rail crossing setting.

There is a need for communication technology based safety applications at passive grade crossings. It is important to communicate both ways: train-to-vehicle and vehicle-to-train. It would be useful to conduct a research survey on communication solutions proposed for passive grade crossings.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (time frame within 2 years) research activities

No near-term activities are recommended for this area because it was deemed a lower priority by the CTCS stakeholders.

Mid-term (timeframe 3-5 years) research activities (can be concurrent)

1. *Connected intersection with rail crossing*. Operational deployment of the connected infrastructure with sensing at an intersection with a rail crossing.

   - *Short Description*: This project will deploy an operational intersection with sensing, interpretation of sensor measurements, and connectedness. The investigation focus will aim at coordination between rail and other crossing agents.
   - *Deliverables*: Field deployment of a connected intersection; and a methodology for a quantitative assessment of its performance.
   - *Dependencies*: Project "Connected intersection with X2I in operation" (Section 4.3.1).
   - *Duration*: 30 months.
   - *Budget*: $1.5-2M.

Long-term (timeframe 6-10 years) research activities

The research above would advance the application of connected infrastructure to rail crossings from TRL 5 to TRL 7 – prototype demonstrated in operational environment. In the longer term, more connected intersections would need to be deployed at rail crossings, and the technology would need to be refined based on lessons learned and more widely adopted in order to bring this application to a TRL 9.

4.5 CONNECTED VEHICLE INTEGRATED CORRIDOR MANAGEMENT (ICM)

This use case explores how connectivity will allow vehicles to interact with traffic, maintenance, transit emergency, and other management systems to determine operational decisions along corridors. The use case will leverage historical, real-time, and predictive sources of information (from these management systems) to determine operational strategies that minimize operational impacts along the corridor(s).
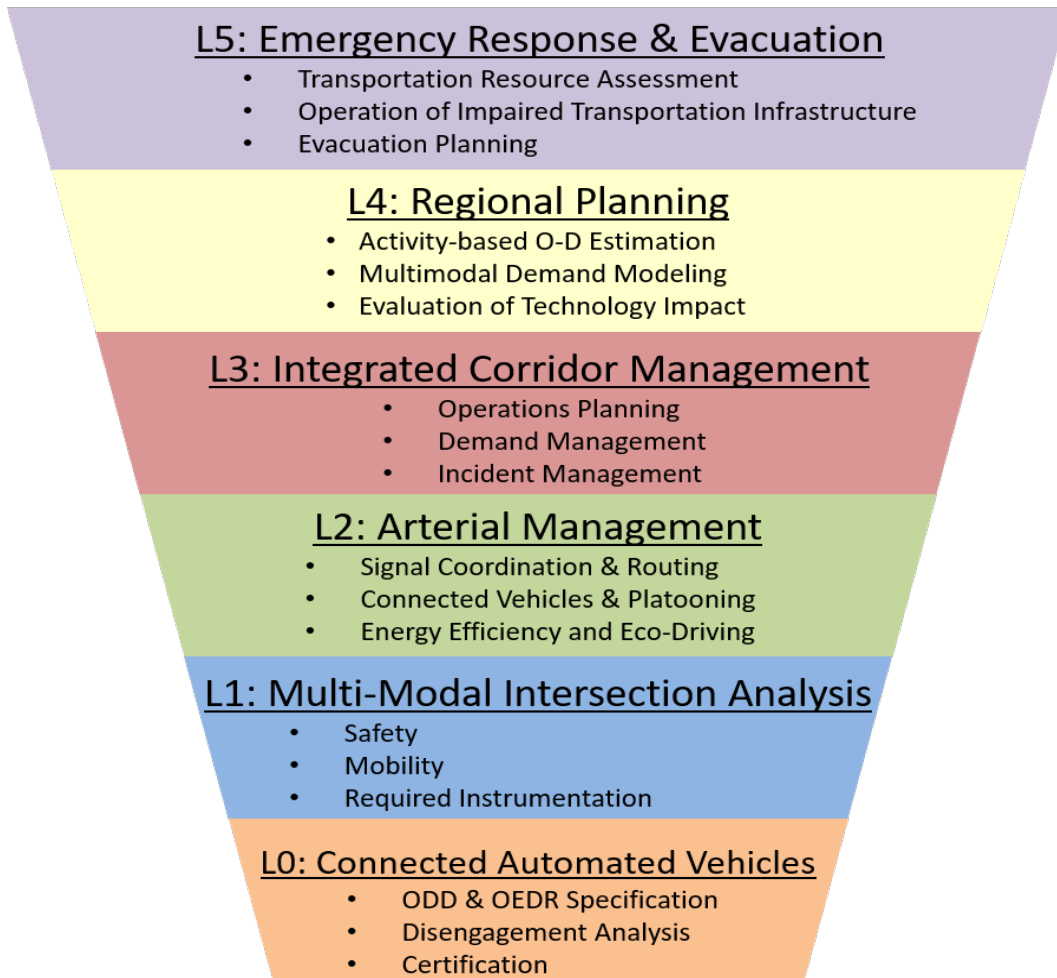
The priority research area within this use case is data sharing.

4.5.1 DATA SHARING

BACKGROUND

Multiple layers of transportation engineering functions are being practiced at public transportation agencies, as shown in Figure 4-2.

Figure 4-2: Layers of Transportation Engineering in Practice

At every layer, transportation engineers rely on geographic information systems (GIS) and additional data needed to analyze current system performance and to model hypothetical scenarios evaluating the quality of system management and its response to exogenous events. Each layer has its own data requirement. These layers can be considered in terms of granularity of analysis in models used by transportation engineers:

- L0 – behavioral, where the behavior of an individual vehicle (or CAV) is considered;

- L1 – nanoscopic, describing vehicle, cyclist and pedestrian trajectories and their interaction;

- L2 – microscopic, where car following and lane changing behavior are important;

- L3 – mesoscopic, where we operate with multi-modal traffic flows;

- L4 – macroscopic, as it deals with average equilibrium flows; and

- L5 – should work on all levels of data granularity.

Generally, data collected and possible analysis output produced at a lower level are used as parameters for the higher layer data analysis or simulation; while data collected and analysis output produced at a higher level are used as input for the lower-level analysis. Also, data required at multiple layers often overlap (e.g., L2 and L3). However, the degree of cooperation in data sharing among agency departments and different agencies depends on personal relationships and awareness of what one's neighbor is doing. Moreover, even when with the high

degree of cooperation, the data exchange is inefficient because modeling and analysis tools used by different departments and agencies and their data formats are often incompatible.

There are many operational examples of very useful real-time transportation data repositories in the country, including Regional Integrated Transportation Information System (RITIS - https://ritis.org), Caltrans Performance Measurement System (PeMS - http://pems.dot.ca.gov), and TRANSCOM (https://www.xcm.org) - to name a few. The idea of open transportation data is nothing new, and significant independent efforts around the country exist, allowing researchers to build on these use cases and to determine best practices. That said, the integration of CV data into these data repositories is still in its nascent stage.

Based on these developments, this research area is TRL 6. Data sharing among agencies was ranked 7th in terms of priority in the CTCS stakeholder workshop.

RESEARCH NEEDED

The examples of transportation data repositories mentioned above use their proprietary data formats and readily serve as data distributors for registered users, but their data acquisition channels are closed and ad-hoc.

To enable an efficient transportation data acquisition, sharing, and exchange at all levels, the following must be considered:

1. ICM applications require the following data:

   - high resolution (5-minute) traffic volumes and speeds on road sections that are part of the integrated corridor;

   - ramp metering rates;

   - signal timing plans for signalized intersections in the integrated corridor;

   - queue estimates at intersections and on-ramps;

   - information about work zones;

   - information about incidents;

   - information about special events;

   - transit schedule;

   - parking information near transit hubs;

   - school hours (if there are schools near the integrated corridor);

   - CAV data that can be utilized for traffic control (e.g., vehicle queue estimates at junctions, delays at ramp meters, unexpected lane closures, etc.).

   Developing a standard data model that would accommodate this information would allow it to be shared between stakeholders and served to CVs.

2. As discussed in Section 3.1, data management project NCHRP 20-102(14) focuses on how data should be managed in a CAV environment. This project has not started yet, but it is funded and expected to begin later in 2019. Going forward, it should be monitored and its results should be considered in future PFS work. The *Using Third Parties to Deliver I2V* project, currently underway as part of the CV PFS funding, also must be factored into future research decisions.

3. Open Transportation Data (OTD) format - a standard that could be used to exchange data as well as planning/simulation/prediction models. The format specification will allow various levels of detail ranging from nanoscopic to macroscopic depending on the type of analysis and modeling, and if it utilizes existing standards, such as OpenDRIVE (http://www.opendrive.org). The idea is to create a standard similar to

Google's GTFS (https://developers.google.com/transit/gtfs) that is now used by most transit agencies to share information about their schedules and trips. GTFS started as a pilot project that snowballed into becoming a nationwide standard.

4. OTD exchange platform that can be used to build transportation data hubs, which will contain a database for storing collected transportation data and a data ingestion mechanism. This platform can have a connection to OpenStreetMap (http://osm.org) with ability to export selected datasets to OpenStreetMap format and to publish at OpenStreetMap. The high-level reference design of the OTD platform is presented in Figure 4-3.
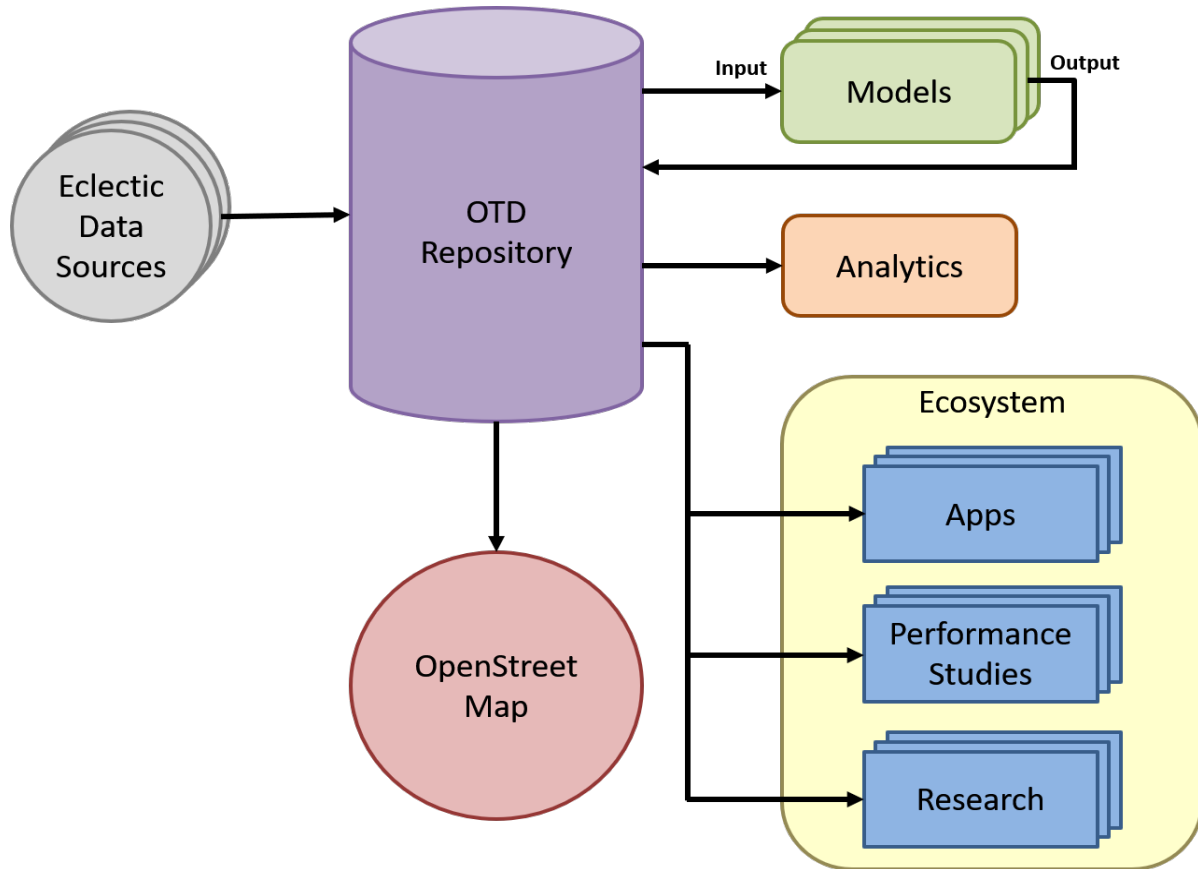
Figure 4-3: OTD Exchange Architecture

RECOMMENDED RESEARCH ACTIVITIES

A range of research activities can be formulated as projects in this area. The previously mentioned NCHRP 20-102(14) project is a near-term effort that should be monitored. Also, two new efforts are recommended as mid-term projects.

Short-term (time frame within 2 years) research activities

No new near-term activities are recommended for this area but NCHRP 20-102(14) is a funded near-term effort that should be monitored.

Mid-term (timeframe 3-5 years) research activities

1. *Transportation data exchange survey*. Survey of transportation data exchanges that include CV data: Data sources, data customers, data formats, best practices. This project should come before any significant data sharing development effort.

- *Short Description*: This project will find and review transportation data hubs. Of special interests are sites where users can upload their data to share with the rest of the community. Data exchange formats and the best practices will be investigated.
- *Deliverables*: A whitepaper describing current transportation data exchange hubs and the best practices.
- *Dependencies*: None.
- *Duration*: 12 months.
- *Budget*: $75-100K.

2. *Intersection MAP repository*. Development of intersection MAP repository for US Cities. Duration: 18 months. Budget: $750-950K. This project depends on a clearer MAP definition (see Section 4.2.1) and should follow that research. Keep in mind that any project requiring the delivery of an information system must consider the future spending on its operations and maintenance. This project would advance the data sharing from TRL 6 to TRL 8 – technology proven in operational environment.

   - *Short Description*: This project will develop an accessible data repository for U.S. intersection MAP configurations. This repository will have an upload as well as search capabilities.
   - *Deliverables*: Publicly available web-based information system with intersection MAP data.
   - *Dependencies*: Project "Guidance on MAP creation" (Section 4.2.1).
   - *Duration*: 18 months.
   - *Budget*: $750-950K.

<u>Long-term (timeframe 6 to 10 years) research activities</u>

Additional research in this area beyond the projects described above is not recommended because the technology will be at a TRL 8 once those projects are completed. At that point, it will largely be up to industry to adopt the technology on a wider scale.

4.6 LANE MANAGEMENT

This use case explores how connectivity will allow vehicles to interact with ITS field equipment (detection, dynamic message/lane control signs) to manage and control specific lane use. Under this use case, lane controls could be automatically controlled based on measured traffic conditions and demand along arterial corridors or used to change the lane configuration of the roadway, use of shoulders as temporary travel lanes, and/or prohibit or restrict types of vehicles from using particular lanes.

The priority research areas within this use case are lane-level dynamic mapping and lane availability.

4.6.1   LANE-LEVEL DYNAMIC MAPPING

BACKGROUND

The SAE J2735 MAP includes static information about intersection/lane geometry as well as dynamic lane attributes such as time-based restrictions (e.g., no left-turn between 7 am - 9 am), reduced speed limit and lane closure in the presence of work zones or due to weather changes and traffic incidents, and temporary shoulder use that adapts roadway capacity to high traffic volumes on a temporary basis. Research needs for detecting the changes of intersection/lane geometry due to changes of satellite images or road pavement are addressed in Section 4.2.1 and the strategies to dynamically determine lane use and control are addressed in Section 4.6.2. This section addresses the research needs for conveying dynamic MAP information together with the static MAP information through layered messages, i.e., a static layer (J2735 MAP) describing intersection/lane geometry, lane width, and posted speed limit, and a dynamic layer (J2735 BIM and/or RSM which are under development) describing dynamic intersection/lane attributes that are referenced to the static layer MAP messages.

Lane-level dynamic mapping is assessed to be a TRL 4 because the layered MAP structure has not been implemented and demonstrated in real-world conditions. Lane-level dynamic mapping was ranked 9th in terms of priority in the CTCS stakeholder workshop.

RESEARCH NEEDED

Creating and maintaining the static J2735 MAP files is already a challenge, and adding the dynamic layer information into the static layer makes it an even bigger challenge for implementations and operations. For example, consider a work zone at a signalized intersection as an example where multiple lanes are closed in the presence of the work zone and multiple lanes require a reduced advisory speed limit for the safety of road workers and moving traffic through the work zone. Recreating a MAP that combines the static intersection/lane geometry and the dynamic work zone information into a single message adds tremendous burdens for IOOs to manage the work zone. Because the intersection is already broadcasting J2735 MAP messages that describe the static intersection/lane geometry, a layered MAP structure that conveys the dynamic work zone information in a separate message referenced to the static layer information is more appropriate. The separate message (e.g., BIM or RSM) describes which lane(s) of the intersection and what portion of the lane(s) (e.g., the location of start and end point of the lane closure with respect to the stop-line) are closed due to the work zone, which lanes and what portion of the lane(s) have a reduced speed limit, and the presence of road workers in the work zone. The vehicle-resident applications are able to combine the dynamic layer information with the static layer information for driver assistance and/or vehicle automation. Upon the completion of the road work, the intersection can stop broadcasting the dynamic layer information without interruption and modification of the static layer broadcasts.

Research to advance the TRL of this topic could include:

1. How the intersection mapping information can be decomposed into static and dynamic layers within the current J2735 standard and collaborate with the underdeveloped BIM and RSM messages;

2. How to create the dynamic layer information preferably with automated or semi-automated tools. An example of such a tool is a web-based work zone builder where an authorized road worker visualizes the static layer information on a tablet; the static layer information (i.e., the J2735 MAP) is either received by an OBU or stored on web server; the web-based tool uses the Geolocation API of HTML 5 and displays the location of the road worker (i.e., the tablet) on the MAP, and provides a graphic user interface (GUI) to input work zone related parameters; the tool is then encoded the work zone information into an appropriate message and sends the message payload to the corresponding intersection for broadcasting;

3. How third-party data, such as HERE and Google Maps traffic conditions and incident data, and fused virtual detection data, can be used to detect the location and range and estimate values of data elements of the dynamic layer information; and

4. How the dynamic layer information (e.g., work zone) can be fed and integrated with navigation tools such as Google Maps and Traffic such that the information can be accessed and used by a wider range of road users in trip planning and en-route detours to avoid the work zone. Integrating lane-level work zone information with existing navigation tools also increases public awareness and acceptance of the CV deployment.

RECOMMENDED RESEARCH ACTIVITIES

Short-term (time frame within 2 years) research activity

1. *Improve BIM and RSM standards*. Combine the standard development of BIM and RSM on layered structured mapping information.

   - *Short Description*: This project will cooperate and leverage ongoing efforts on BIM and RSM standard development to incorporate layered structured mapping information in BIM and RSM message definition.
   - *Deliverables*: A document describing the recommended layered structured mapping information.

- *Dependencies*: Ongoing efforts on BIM and RSM standard development.
- *Duration*: 12 months
- *Budget*: $100K

Mid-term (time frame 3 to 5 years) research activities

1. *Web app for dynamic layer mapping*. Develop a prototype web-based tool for creating the dynamic layer mapping information based on the static layer mapping information.

   - *Short Description*: This project will develop a web-based tool for IOOs to create the dynamic layer mapping information such as lane closure due to work zone or accidents at connected signalized intersections. The dynamic layer mapping information is referenced to the static layer mapping information (e.g., MAP broadcasts at the intersection) as described in Research Needed above. The web tool could utilize the MAP creation tool (Section 4.2.1) for visualization of the static layer mapping information of the intersection and utilize RTCM broadcasts at the intersection to get a better positioning of the road worker who is creating the dynamic layer mapping information (Section 4.2.3).
   - *Deliverables*: A web-based tool implemented in software and a user manual of the tool.
   - *Dependencies*: Project "Improve BIM and RSM standards", Project "Improve the MAP creation tool" (Section 4.2.1), and Project "RTCM for a better localization" (Section 4.2.3).
   - *Duration*: 18 months
   - *Budget*: $150K

Long-term (time frame 6 to 10 years) research activities

The completion of the two listed projects would advance lane-level dynamic mapping from TRL 4 to TRL 6 – Prototype demonstrated in a relevant environment. The next step would be research on cooperative perception where vehicles share local perception information among themselves and with infrastructure to improve the effectiveness and deployability of lane-level dynamic mapping.

4.6.2   LANE AVAILABILITY

BACKGROUND

Lane management strategies include:

- Lane use control, when a lane dedicated to a certain type of traffic, e.g. buses or high occupancy vehicles (HOVs), is opened for general use, which may happen when such a lane is significantly underused.

- Lane reversal, when certain lanes may switch direction depending on the traffic demand: capacity increase in one direction decreases the capacity in the opposite direction.

- Dynamic shoulder lane, when a lane dedicated to a street parking or a freeway shoulder is opened to general traffic, which may happen when extra capacity is required on certain road links to prevent them from becoming bottlenecks.

- Warnings about lane closure ahead due to accidents or construction.

Presently, lane management is through dynamic message signs and road zippers. Preliminary research about the use of V2X for lane management is underway. Some operational scenarios were evaluated using traffic simulation software. SAE J2735 MAP and SPaT messages can provide information about lane availability through dynamic lanes defined in the MAP message and activated by data in the SPaT message. The readiness of this technology is at the level of component validation in the lab environment (TRL 4). Lane availability was ranked 10th in terms of priority in the CTCS stakeholder workshop.

RESEARCH NEEDED

In this research area, several major questions must be addressed for the technology to advance to the next level:

1. What are the compelling use cases for the lane management through V2X as opposed to the current dynamic message signs? An example could be an emergency response and evacuation when unusual measures are in order, including contraflow operations, and dynamic message signs may not be available.

2. What should be the penetration rate of CVs for the V2X-based lane management to make a significant impact? The answer should be a formula or an algorithm computing this penetration rate based on the road geometry, demand, and the desired impact rather than a single number.

3. What are the safety implications for the unconnected traffic that starts using the managed lanes visually following the actions of CVs? Especially important is the situation when special lanes close. In this case, CVs can be directed to leave the lane, whereas the unconnected traffic will remain uninformed.

4. How can CVs be used for speed harmonization and vehicle flow control upstream of the closed lane(s)? Lane closures may happen due to road work or accidents. Such closures usually create bottlenecks that cause capacity drop on the remaining lanes. To avoid or minimize this capacity drop, the upstream traffic flow must be harmonized. This research is related to MAP - lane-level dynamic mapping (Section 4.6.1).

RECOMMENDED RESEARCH ACTIVITIES

Short-term (time frame within 2 years) research activities

No near-term activities are recommended for this area because it was deemed a lower priority by CTCS stakeholders.

Mid-term (timeframe 3 to 5 years) research activities (can be concurrent)

1. *Application of V2X to dynamic lane control*.

   - *Short Description*: This project will determine the feasibility of V2X application for lane management and the conditions when such an approach will be effective (e.g., what should be the penetration rate of CVs for the V2X-based lane management to make a significant impact?). It will also address the safety issues, such as the situation when special lanes close. In this case, CVs can be directed to leave the lane, whereas the unconnected traffic will remain uninformed.
   - *Deliverables*: Simulation based study.
   - *Dependencies*: None.
   - *Duration*: 15 Months.
   - *Budget*: $100K.

2. *Application of V2X for speed harmonization and traffic flow control ahead of temporary lane drops*.

   - *Short Description*: This project will determine how CVs can be used for speed harmonization and vehicle flow control upstream of the closed lane(s)? Lane closures may happen due to road work or accidents. Such closures usually create bottlenecks that cause capacity drop on the remaining lanes. To avoid or minimize this capacity drop, the upstream traffic flow must be harmonized.
   - *Deliverables*: Simulation based study.
   - *Dependencies*: CTCS Project "Improve BIM and RSM standards" (Section 4.6.1).
   - *Duration*: 15 months.
   - *Budget*: $100K.

These research activities would advance the technology from TRL 4 to TRL 5 – integrated components demonstrated in a laboratory environment.

Long-term (6-10 years) research activities

Long-term activities in this area will depend on the research needs that are determined during the completion of the suggested mid-term activities. As such, the long-term research activities will be identified after the mid-term projects are completed.

5 CONCLUSION AND NEXT STEPS

As this report documents, there are numerous opportunities to further the research for all the identified use cases and prioritized research areas within the CTCS domain. The project team recommends research activities for each CTCS area ranging from studies, white papers, and design work to prototype development and field tests. For most recommended research activities, the project descriptions provided in this report must be further refined and formulated, with more detail being provided to the scope, budget, and schedule.

Looking ahead, PFS and FHWA must carefully consider the CTCS research roadmap when making future CAV project funding decisions. As funds become available, many of the project ideas in this research plan could form the basis of future projects. Priorities and suggested sequencing are assigned to the projects in this research plan to aid in the selection process but it will ultimately be up to PFS or FHWA to decide which projects to fund and when to fund them.

For one specific CTCS research area, Queue Length Detection, the current CTCS project will go into greater detail in Task 6 by developing a concept of operations (ConOps) A ConOps documents the characteristics or features of a proposed system from the user's viewpoint, which includes the infrastructure owner/operator but may also include road users and others. Development of a ConOps is a critical early step in the systems engineering process because it often forms the foundation for future R&D activities.

The project team selected Queue Length Detection as best suited for ConOps development for three reasons. First, as discussed earlier, this research area ranked 1st in terms of priority during the April stakeholder meeting in Ann Arbor. Second, when the project team completed the literature review task and review of current activities, the TRL associated with this proposed research area was deemed to be a TRL 5. Under normal circumstances a TRL 5 would not warrant a ConOps, but because the work related to Queue Length Detection has primarily been focused on freeway applications, and because stakeholder interest is focused on signalized arterials, the TRL must be calibrated down to TRL 3, justifying the need for the ConOps. Finally, for Queue Length Detection, the roadmap in Section 3 shows the next step is a design/simulation activity and developing a high-level ConOps prior to this type of activity lays a good foundation for future work.

As such, Task 6 of the current CTCS project will develop a high-level concept of operations for Queue Length Detection. Given the limited time and resources remaining on the current project, this ConOps must be written as a high-level document and have a limited amount of stakeholder input. Nevertheless, it will serve as an important milestone and lay the groundwork for the next steps on the research roadmap for this high priority area.

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