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

Task 3: Research Review

Final

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1 INTRODUCTION

1.1 BACKGROUND

The University of Virginia (UVA) Center for Transportation Studies (CTS), on behalf of the Connected Vehicle Pooled Fund Study (CV PFS) and the United States Department of Transportation (USDOT), understand the intrinsic value in advancing Multi-Modal Intelligent Traffic Signal System (MMITSS) research efforts towards Connected Traffic Control System (CTCS) concepts.[1] As government and industry move to embrace connected and automated vehicle (CAV) technologies, there is need to progress towards next generation research that more fully integrates transportation systems management and operations (TSMO) with CAV technologies that are continually emerging to further improve safety, mobility, and the environment. This includes continuing to work to advance the understanding of how connected vehicle (CV) technologies interface with all transportation network infrastructure and to understand how to best plan for the introduction of automated vehicles (AV) within this environment.

Accomplishing this goal requires an in-depth understanding of the context, status, and outcomes of research already conducted by the various USDOT modal administrations, other related research organizations, and the private sector. These efforts must then be considered in the context of intelligent transportation systems (ITS), TSMO, and CAV to understand and ultimately deliver integrated traffic control concept(s) that includes arterials and interchanges – incorporating increasing levels of vehicle automation along the way. To this end, this report examines foundational research that has already been conducted and defines a basis for future research that builds off previous and ongoing research activities in an iterative fashion to remain flexible in accommodating institutional, political, and rapidly evolving technical changes.

1.2 PREVIOUS MULTI-MODAL INTELLIGENT TRAFFIC SIGNAL SYSTEM DEVELOPMENT EFFORTS

Phase I

The USDOT has identified six mobility application bundles under the Dynamic Mobility Applications (DMA) program for the CV environment where high-fidelity data from vehicles, infrastructure, pedestrians, and other roadway objects can be shared through wireless communications. Each bundle contains a set of related applications that are focused on similar outcomes. Since a major focus of the CV PFS members – who are the actual owners and operators of transportation infrastructure – lies in traffic signal related applications, the CV PFS team is leading the project titled Multi-Modal Intelligent Traffic Signal System (MMITSS) in cooperation with USDOT's Dynamic Mobility Applications Program. As one of the six DMA application bundles, MMITSS includes five applications: Intelligent Traffic Signal Control (I-SIG), Transit Signal Priority (TSP), Mobile Accessible

[1] The CV PFS was developed by a group of state and local transportation agencies and the Federal Highway Administration (FHWA). The Virginia Department of Transportation (VDOT) serves as the lead agency and is assisted by the University of Virginia's Center for Transportation Studies, which serves as the technical and administrative lead for the PFS.

Pedestrian Signal System (PED-SIG), Freight Signal Priority (FSP), and Emergency Vehicle Preemption (PREEMPT).[2]

The first phase of the MMITSS project was divided into four technical segments. The development of the Concept of Operations (ConOps), including the solicitation of Stakeholder inputs and feedback, was the first technical stage. The reviewed Stakeholder inputs and ConOps were used to develop, define, and populate the MMITSS system requirements in the second technical stage. In the third stage, the system requirements and prior research were used to define the MMITSS system design. The design effort utilized the California test bed and the Arizona test bed as the target implementation networks. The final stage included Detailed Design, System Implementation and Integration, Field Integration and Testing, and a System Demonstration in each of the California and Arizona test beds.

Phase II

The Phase II MMITSS development, field testing, and demonstrations resulted in two MMITSS prototypes that realized advanced traffic control in a CV environment. The MMITSS prototypes, one in Arizona (AZ) and one in California (CA), implemented innovative traffic control algorithms that utilized the rich data available from CVs. The Arizona MMITSS prototype utilized concepts from adaptive and priority-based traffic signal control together with the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) standard for communications to state of the art traffic signal control equipment. The California MMITSS prototype utilized enhancements to legacy traffic signal controllers where the control logic resided within the California Department of Transportation (CalTrans) 2070 controller firmware, but with adjustments made based on CV data. These accomplishments, including the implementations in the two test beds, have created a valuable platform for additional development and field evaluation that can provide understanding and knowledge that is necessary for improvement of traffic signal operations in a CV environment, and that will support future development to address more complex traffic management needs and opportunities.

However, several of the use cases identified in the MMITSS Phase I were not implemented in the MMITSS Phase II effort. These use cases documented advanced Stakeholder Needs that were identified in the Phase I Stakeholder Needs Assessment activities and at the time, were recommended for inclusion as part of future enhancements of MMITSS.[3] These use cases included:

- Congestion Control
- Nearside Bus Stops
- Transit Priority for Left Turn
- Operational Scenarios for Rail Crossings in Urban Areas
- Equipped Bicyclist(s)
- Inclement Weather Accommodations for Non-Motorized Travelers
- Coordinated Freight Signal Priority along a Truck Arterial
- Route Based Intersection Priority/Preemption

This list provided a starting point for the CV PFS members and other stakeholders to identify priority use cases that are the focus of the research plan developed as part of the CTCS project. Several of these use cases continue to have the support for future research, including being featured in the use cases identified in this report (first introduced in Section 1.3 below).

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[2] http://www.its.dot.gov/research_archives/dma/dma_plan.htm

[3] University of Arizona, University of California PATH Program, Savari Networks, Inc., and Econolite. *Multi-Modal Intelligent Traffic Signal System – Phase II: System Development, Deployment and Field Test.* Pp. 158

Phase III

Phase III of MMITSS, which is currently ongoing, is focused on revising the prior research and prototypes that were developed and field tested in Phase II and making them deployment ready. The readiness enhancements are focused on creating mature, application code that is hardware agnostic and interoperable or transferable regardless of the hardware vendors or products. To achieve these goals, the project team (University of Arizona and California PATH program) are performing or intend to perform the following:

- Improve the MMITSS software manuals, including the requirements on the host platforms and compilers, the download and build instructions, software design documentation, and specification of an API for the roadside unit (RSU) Dedicated Short Range Communication (DSRC) interface that vendors can implement to support interoperability.
- Increase the source code maturity through code reviews with the MMITSS Development Group of stakeholders, including changes that make the source code hardware agnostic.
- Carry out additional development of essential functions for MMITSS through field testing for improvements and fine tuning.
- Identify enhancements required for deployability, including upgrading to the 2016 SAE J2735 message set, and field testing of traffic control enhancements including coordination (for both MMITSS--AZ and MMITSS--CA).

While the Phase III effort doesn't necessarily serve to specifically expand the use cases that MMITSS currently supports, the call to 'harden' the prototypes clearly demonstrates the interest by the stakeholder community in the MMITSS concept, and by proceeding with Phase III, it also better enables the MMITSS framework to support additional further enhancements such as those that may results from the CTCS research.

1.3 SCOPE

The focus of this report is to investigate and assess the prior and ongoing research activities related to traffic control solutions which leverage CAV technologies, and which extend beyond the individual signalized intersection that is a focus of the current MMITSS research, to include other functions and applications that build from the MMITSS concepts and promote mobility between intersections and adjacent freeway/ramp/arterial networks. This assessment addresses domestic research activities, those conducted internationally (in Europe as well as other continents), and the involvement of technology vendors, including communications firms. This includes research into existing applications that have broader implications to control between signalized intersections but also includes new applications emerging as a result of new technologies. The analysis contained in this report is structured around previously agreed-to "use cases" as identified in the CTCS Task 2 report. These uses cases, which are defined as a list of actions that define the interactions between a user and a system to achieve a specific goal, include:

- **Arterial/surface streets with traffic control and ramp meters** - This use case explores how connectivity will allow vehicles to interact with ITS technology beyond the individual traffic signal controllers, such as ramp meters, adaptive signal systems, etc., in order 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.
- **Multi-modal aspects including transit, freight, pedestrians, bikes, etc.** - This uses case explores how connectively will allow transit and freight vehicles, as well as non-motorized modes, to interact with other vehicles, pedestrians, and roadway field devices to improve multi-modal operations along a corridor(s). This use case currently represents a bundle of potential services.
- **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 could leverage vehicle-to-vehicle (V2V) communications to enable vehicle platooning but also vehicle-to-infrastructure (V2I) communications to communicate the arrival of vehicle platoons to intelligent transportation system (ITS) field equipment – mainly traffic signal controllers.

- **Connected vehicle integrated corridor management** - 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).
- **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, allow use of shoulders as temporary travel lanes, and/or prohibit or restrict types of vehicles from using particular lanes.
- **Railroad crossing violation warning** - This use case explores how DSRC technology might be used to improve safety at grade-level rail crossings, particularly in cases of unsignalized crossings in rural locations, or in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic.

This report also identifies and documents gaps in current and ongoing research that sets the stage for future research.

Finally, the report served as the basis for the content and feedback gathered from the in-person Stakeholder Workshop conducted on April 30, 2019 as part of Task 4. Upon completion of the workshop, the final version of this report was modified and finalized, for publication on the CV PFS website.

1.4 METHODOLOGY

The methodology employed in this research review is structured around the analysis of potential use cases identified by the research team with concurrence from the CV PFS. A structured internet search was conducted to identify initiatives including studies, research and development (R&D), and deployment activities related to the above list of use cases. Initiatives included those sponsored by USDOT, non-government organizations (NGOs) such as that National Cooperative Highway Research Program (NCHRP) and American Association of State Highway and Transportation Officials (AASHTO), colleges and universities, as well as international organizations such as ERTICO – ITS Europe. These initiatives were then summarized in terms of the research and/or development activities that were initiated, the relevance to the CTCS research planning activities, and key outcomes and findings. Identification of previous and ongoing activities was further aided through the engagement of subject-matter-experts, including those on the research team and members of the PFS.

A high-level Technology Readiness Level (TRL) assessment was also conducted to define a clearer picture of current research as it relates to the identified applications. A TRL assessment is a systematic, metrics-based process that assesses the maturity and potential risks of critical technologies. TRLs were originally conceived at NASA in 1974 and formally defined in 1989.[4] TRL assessments are based on a scale from 1 to 9, with 9 being the most mature technology. The Federal Highway Administration (FHWA) employs the concept of TRL to assist in the prioritization of research activities. A 2017 Exploratory Advanced Research (EAR) project performed by the

[4] https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html

Volpe National Transportation Center documented how to apply and what not to use TRL for in context of the transportation projects.[5] In the context of this effort, TRL assessments are used as tool to help establish a path for future CAV research, including that envisioned under CTCS.

1.5 DOCUMENT ORGANIZATION

This research review is organized into the following sections:

- Section 2, Previous and Ongoing Research and Development Efforts - Provides an overview of previous and ongoing research activities as they relate to developing the CTCS research plan.
- Section 3, High-Level Technology Readiness Assessment – Provides a high-level Technology Assessment based on the analysis of previous and ongoing research as it relates to identified use cases.
- Section 4, Key Findings and Next Steps – Provides a summary of this report and identifies the major gaps as it relates to the identified use cases. It also sets the stage for the Task 4 work, including stakeholder refinement of these topics.

[5] https://www.fhwa.dot.gov/publications/research/ear/17047/001.cfm#Toc516141870

2 PREVIOUS AND ONGOING RESEARCH AND DEVELOPMENT EFFORTS

2.1 ARTERIAL/SURFACE STREETS WITH TRAFFIC CONTROL AND RAMP METERS

This use case explores how connectivity will allow vehicles to interact with ITS technology beyond the individual traffic signal controllers, such as ramp meters, adaptive signal systems, etc., in order 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.

2.1.1 CONNECTED VEHICLE SYSTEM DESIGN FOR SIGNALIZED ARTERIALS[6]

RESEARCH OVERVIEW

This project, led by Dr. Xian Feng Yang, University of Utah, as part of the USDOT UTC program, began in 2018 and is expected to conclude in November 2019. The project aims to establish a real-time and adaptive system for supporting the operations of a CV-based signalized arterial. By establishing the communication needs of different types of CVs, the research looks to explore approaches to best utilize the capacity of the communications channels using a newly developed concept of Age of Information (AoI). The project includes both CV and CAVs and looks to optimize real-time traffic signal plans and vehicle trajectory, including use of transit signal priority for connected buses. The concepts will be evaluated with support by the Utah Department of Transportation (UDOT).

RELEVANCE TO CTCS RESEARCH

Communication limits between infrastructure and vehicles in a CV environment have not yet been fully quantified, but it is a common belief that as the number of connected devices continues to grow, the demands on the infrastructure have the potential to impact connectivity and latency. One of the areas that would be impacted by this limitation is that of enhanced corridor management. Not all vehicles approaching on multiple approaches can be considered equally. By understanding the communication needs and limits and classifying vehicles relative to these needs and presumed priority, the effectiveness of strategies using this information can be better refined. CTCS, as an implementation of an enhanced MMITSS concept would have to consider these same impacts.

[6] https://nitc.trec.pdx.edu/research/project/1235

KEY OUTCOMES

- This project is still in progress, however, as UDOT is a member of the PFS, and as UDOT is also deploying MMITSS, any connection between the projects would be useful to better understand.
- The concept of classifying and prioritizing the different communication needs, and concepts on how those different classes/needs are used to support enhanced corridor management strategies is in-line with CTCS concepts. Identifying the criteria to create the classification could prove valuable.

2.1.2 DEVELOPMENT OF ECO-FRIENDLY RAMP CONTROL BASED ON CONNECTED AND AUTOMATED VEHICLE TECHNOLOGY [7]

RESEARCH OVERVIEW

This project, led by Dr. Guoyuan Wu, University of California, Riverside, and expected to be complete in June of 2019, intends to research a hierarchical ramp merging control strategy which will first consider mainline traffic information to determine entrance rates of ramp traffic and then control speeds of (both mainline and on-ramp) CAVs without unnecessary stops to achieve desired entrance rates while maintaining safe gaps during merging.

RELEVANCE TO CTCS RESEARCH

Preliminary engagement with PFS members has identified Ramp Metering in association with a broader corridor management strategy as an item of interest for future research. This particular research proposes to reduce the impact of on-ramp queues and merging traffic, both of which are related to both the ramp-metering itself, but also the feeder arterials which lead to the ramp. Immediate relevance to CTCS Research is not presently known, but at least on the initial scan, it may be prudent to further review the work products of this work.

KEY OUTCOMES

- This project is still in progress and will require further outreach before significant outcomes can be delineated.
- The team would need to explore if the approach to monitor both the mainline and ramp volumes are based on CV-technology, and to then consider how the inclusion of the ramp meter in conjunction with the arterial signalization and corresponding queue monitoring may be improved by the use of CV.

2.1.3 UTILIZATION OF CONNECTED VEHICLE DATA TO SUPPORT TRAFFIC MANAGEMENT DECISIONS[8]

RESEARCH OVERVIEW

This 2017 report prepared by the Lehman Center for Transportation Research at Florida International University and Southwest Research Institute discusses the relationship between CVs, vehicle-to-infrastructure (V2I) technologies, and the data communicated between these applications in support of Florida Department of Transportation's (FDOT) SunGuide's traffic management center (TMC) operations. It provides a review of nine

[7] https://ncst.ucdavis.edu/project/development-ecofriendly-ramp-control-based-connected-automated-vehicle-tech/

[8] https://rosap.ntl.bts.gov/view/dot/35836

SunGuide functions that illustrate how CV data can be used for SunGuide advance transportation management system (ATMS) modules. Currently, CV data can be used to support ramp metering and its fuzzy logic algorithm. CV data is advantageous in that it shows when vehicles are arriving and provides more accurate data on vehicle gaps for on-ramp rates. In addition, Kattan and Saidi (2013) created a probe-based adaptive ramp metering approach based on CV data and proved that its algorithm outperformed traditional algorithms that do not use CV data. University of Virginia Center for Transportation Studies also investigated the use of CV data and found that the CV data-based algorithm improved ramp metering performance but requires high compliance between drivers and almost a full deployment of CVs to achieve these benefits. Another technology researched in conjunction with ramp metering was Cooperative Adaptive Cruise Control (CACC), which was used for Cooperative Ramp Metering. Simulation showed a reduction in the level of congestion.

RELEVANCE TO CTCS RESEARCH

FDOT has found that by combining CV data together with point detector data, it will increase efficiency in ramp metering since this will provide actual vehicle arrival time and distances between each other to the Fuzzy Logic algorithm. In comparison to detector-based and pre-timed ramp metering algorithms, this CV data-based result led to higher ramp metering performance at penetration rates of 3% and higher. In addition, they found that using CV data-based algorithms improved ramp metering performance by 4.3% more vehicle miles traveled and 4.6% less vehicle hours traveled, which led to 9.3% higher average speeds. Also, they found that vehicles equipped with CACC technology experienced less congestion and better merging maneuvers between 50-70% based on the strategy Cooperative Ramp Metering (CoopRM). CTCS will need to consider the integration of both CV and traditional detectors to optimize the ramp metering strategy.

KEY OUTCOMES

Key outcomes of this research are:

- Ramp metering combined with CV data-based algorithms led to increased performance metrics of 4.3% more vehicle miles traveled and 4.6% less vehicle hours traveled.
- CACC technology leads to less congestion and better merging maneuvering for vehicles.

2.1.4 MULTI-MODAL INTELLIGENT TRAFFIC SIGNAL SYSTEM – CONCEPT OF OPERATIONS[9]

RESEARCH OVERVIEW

This document, published in 2015, established use cases that are still relevant today, and have been supported by additional research and development. The MMITSS ConOps states the vision and roadmap for the development of the MMITSS program and is based on stakeholder input. It aims to transform current traffic signal systems into a much more efficient and safer traffic signal control system using arterial traffic signal applications identified by the DMA template process and other applications. These include I-SIG, TSP, PED-SIG, FSP, and PRE-EMP. Additionally, input from stakeholder meetings are also considered.

The concept of operations identifies feasible early implementation opportunities and goals that will later be tested on existing testbeds in Arizona and California. Because these test beds utilize different underlying technologies, they will provide a thorough initial test to see the limitations and improvements needed for each application.

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[9] http://www.cts.virginia.edu/wp-content/uploads/2014/05/Task2.3._CONOPS_6_Final_Revised.pdf

RELEVANCE TO CTCS RESEARCH

Currently, existing traffic control systems use traffic signals based on fixed timing or fixed vehicle location detection to moderate the signal lights, while pedestrians are mostly serviced by a pedestrian push button or fixed timing schedule. With the incorporation of MMITSS and CV technology and applications, it can help transform the current system into a safer, more reliable traffic signal control system for users as well as maintain consistency across CV deployments through USDOT. As most of the key components will be based on roadside equipment (RSE) and mobile equipment, such as onboard equipment and nomadic devices, MMITSS focuses on the infrastructure and mobile applications that will help traffic flow.

KEY OUTCOMES

- This report reinforces stakeholder needs for the use cases identified by the original MMITSS research that were not specifically pursued on the subsequent MMITSS research phases.
- Some of these use cases remain important to stakeholders and are being considered for CTCS.

2.1.5 REAL-TIME DETECTOR-FREE ADAPTIVE SIGNAL CONTROL WITH LOW PENETRATION OF CONNECTED VEHICLES[10]

RESEARCH OVERVIEW

This 2018 research paper authored by Feng Y., Zheng J. and Li H., University of Michigan explores the implementation of a real-time detector-free adaptive signal control system with a low penetration of Connected Vehicles. A probabilistic delay estimation model is proposed, which only requires a few critical CV trajectories. An adaptive signal control algorithm based on dynamic programming is implemented utilizing estimated delay to calculate the performance function. If no CV is observed during one signal cycle, historical traffic volume is used to generate signal timing plans. The proposed model is evaluated at a real-world intersection in VISSIM with different demand levels and CV penetration rates.

RELEVANCE TO CTCS RESEARCH

The penetration of connected vehicles is expected to remain low over the next several years, however, agencies deploying roadside CV are interested in finding ways to show value even at this low penetration rate. Similar to MMITSS, this approach uses the trajectories of CV-equipped vehicles to serve as a replacement for traditional fixed-location detectors, and further, given the robust-nature of the network supporting the CV environment, information from multiple, upstream RSUs can be brought together to better determine adaptive strategies.

KEY OUTCOMES

- A CV Penetration of <10% has been determined to be sufficient, via modelling, to allow for adaptive signal timing algorithms to be developed
- Offers potential Day 1 benefits for earlier adopters of CV Infrastructure

[10] http://dx.doi.org/10.1177/0361198118790860

2.1.6 COORDINATION OF FREEWAY RAMP METERS AND ARTERIAL TRAFFIC SIGNALS PHASE IIA – SITE SELECTION AND SIMULATION DEVELOPMENT[11]

RESEARCH OVERVIEW

This research, published in 2016 by Partners for Advanced Transportation Technology (PATH) at the University of California, Berkeley, under contract to CalTrans, investigates the development of a control algorithm for on-ramp metering as an extension of the existing algorithm developed previously for use on a single freeway metered on-ramp with an adjacent isolated signalized intersection. Based on previous research, the research found that past projects involved diverting traffic from freeways to arterials to mitigate congestion without fully looking at day-to-day operations or implementing field tests to evaluate these strategies. Thus, using a 3-mile segment of Interstate-680 from Alum Rock Avenue to Berryessa Road in San Jose, California, they analyzed three (3) control strategies: Ramp-Signal Control, Arterial Green Time Re-allocation, and Queue Length Minimization respectively. Ultimately, they chose strategy III due to its simplicity and feasibility for real world implementation and tested it using a microscopic simulation model.

RELEVANCE TO CTCS RESEARCH

This research is relevant to CTCS since it proves through simulation testing that the control algorithm can lead to improved results using existing surveillance technologies and infrastructure. Although it was only tested through simulation models, it does set the research up to be advanced and tested at the selected test site.

KEY OUTCOMES

Key outcomes of this outreach are:

- Through Queue Length Minimization implementation, they found that it led to more efficient signal timing and system-wide reduced delay of up to 7%.
- Benefits experienced by the arterial can be redistributed to the freeway by deactivating the queue override function of freeway ramp metering.
- Activating queue override reduces the freeway bottleneck capacity by 5-10%.

2.1.7 SCOOP[12]

RESEARCH OVERVIEW

This internet resource documents the test deployment project of cooperative intelligent transport systems in France. SCOOP aims at deploying 3000 vehicles over 2000 km of roads, on five sites: Ile-de-France, Paris-Strasbourg highway, Isère, the ring road of Bordeaux, and Bretagne. Research objectives are:

[11] http://www.dot.ca.gov/newtech/researchreports/reports/2016/CA16-2535_FinalReport.pdf

[12] http://www.scoop.developpement-durable.gouv.fr/en

1. Improving road safety and the safety of road operating agents. Determining the extent to which crashes can be avoided by exchanging basic safety data.
2. Making traffic management more efficient and contributing to the reduction of emissions. Through the collection of data from vehicles and/or infrastructure, C-ITS allows better management and efficiency of traffic information in real time. C-ITS will also play a key role in facilitating modal transfer. New multimodal services for a sustainable mobility (such as dynamic carpooling) will be made available by crossing information relative to Park and Ride sites (such as locations and availability of parking spaces) with information relative to public transportation systems (such as locations of the railway stations, bus stations or multimodal areas).

Vehicles are equipped with sensors to detect events such as a slippery road, an emergency brake, etc. and with on-board units to transmit the information to V2V and to the V2I through road side units. The road operator can also transmit information (road work, etc.) to the vehicles through their on-board units (I2V).

RELEVANCE TO CTCS RESEARCH

Many of the services that will be provided as part of SCOOP could be applicable to use cases that are developed for CTCS. Many of these services are also included as part of other European initiatives. As described in the descriptions of other initiatives, probe vehicle data will assist in use cases where traffic management is involved. Road Work Warning and Hazardous Location notifications could be included as part of a lane management strategy. Assessing traffic information and smart routing services will be useful for developing the CV ICM use case. The Relay Fleets and multimodality service will likely play a role in the development of the use case that handles multi-modal travel. A traveler, when provided with multi-modal alternatives, may decide to change their mode of travel when it is more efficient than their primary mode of travel. Providing these multi-modal options to the traveler improves traveler mobility especially in urban areas where traffic is often congested, and alternative modes of travel are available.

KEY OUTCOMES

Use Cases included in this research are as follows:

- Probe vehicle data - These provide solutions for congestion reduction with data exploitation in both off-line and real-time to improve traffic studies for congestion reduction and to complete knowledge of traffic state for road operator. This involves the collection of data that interests the network operators. It concerns two types of data: traffic data and event data. The data are used to enable other services.
- Road work warning - These are warnings that inform users of roadwork and its characteristics (location, duration of work, etc.).
- Signage applications - This group of services provides users with driving information regarding fixed signage, real-time speed signage, and Virtual Message Signs.
- Hazardous location notifications - These are warnings sent to users when accidents or incidents that have a major impact on safety occur.
- Traffic information and smart routing - This group concerns supplying the user with information that can be used to adapt an itinerary based on the state of traffic and the operator's recommendations.
- Relay Fleets and multimodality - This group offers users an information service on the multimodal transfer possibilities.

2.1.8 SAFETEC

RESEARCH OVERVIEW

Security Assurance Framework for Networked Vehicular Technology (SAFERtec) proposes to define a flexible and efficient assurance framework for security and trustworthiness of CVs and V2I communications seeking to improve the cyber-physical security ecosystem of CVs in Europe. The cornerstone of SAFERtec is to make assurance of security, safety and privacy aspects for CVs, measurable, visible and controllable by stakeholders and thus enhancing confidence and trust in CVs.[13]

RELEVANCE TO CTCS

While SAFERtec prominently focuses on security, the use cases that are used to demonstrate it could be of interest for studying for potentially being applicable to the CTCS. The optimal driving speed advice scenario closely matches the GLOSA application that is applied on numerous other projects throughout Europe. The remainder of SAFERtec scenarios are expected to have limited transferability to CTCS use cases, as the focus on safety, priority at intersections for emergency vehicles, and maintaining privacy when providing directions to a driver. There are certain traffic management control techniques that could be based on the capturing traveler intended route data. While this is not currently common in traffic management, if it were possible to capture the intended route from a portion of travelers, these routes could be aggregated to preemptively implement traffic management strategies to mitigate any predicted adverse condition. In this case, preserving the privacy of travelers while using their data will be important, making this scenario transferrable to CTCS should routing data be used to enable traffic management strategies.

KEY OUTCOMES

Considers a broad range of the related security-assurance issues using the messages exchanged in driving scenarios such as:

- Optimal driving-speed advice. The vehicle can rely on phase and timing messages to calculate and suggest the appropriate speed at which it will reach the intersection at the beginning of the next green phase.
- Provision of real-time traffic-hazard information. Relying on environmental notification messages sent by the infrastructure, a vehicle can avoid rear-end collision as it approaches an already-formed traffic jam (on a highway). In-vehicle functionality is then used to make the driver aware.
- Priority request in intersection-crossing. Authorized emergency vehicles may request priority from the infrastructure that coordinates an intersection. Such requests override normal operation and result in updated signal patterns broadcasted to involved vehicles.
- Privacy-preserving trip planning and navigation. A destination is selected though a web or smart-phone application. Then, a navigation device in the car is synchronized by a cloud-based service to provide the driver with a suggested route.

[13] https://www.safertec-project.eu/

2.2 MULTI-MODAL ASPECTS INCLUDING TRANSIT, FREIGHT, PEDESTRIANS, BIKES, ETC.

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

2.2.1 AUTOMATED AND CONNECTED VEHICLE (AV/CV) TEST BED TO IMPROVE TRANSIT, BICYCLE, AND PEDESTRIAN SAFETY[14]

RESEARCH OVERVIEW

Texas Agricultural and Mechanical (A&M) Transportation Institute (TTI) conducted, in cooperation with TxDOT and FHWA, a study to address safety concerns for bicyclists, pedestrians, and vehicles through AV/CV applications. In addition to case studies, the institution conducted meetings and workshops with stakeholders to review proposed AV/CV applications. A Concept of Operations was then created to focus on feasible, near-term applications.

RELEVANCE TO CTCS RESEARCH

This report reviewed six case studies which involve improving congestion, safety, and vehicle performance through the application of advanced sensor systems and software, many of which have the potential to be supported similarly by AV/CV technology. Those case studies most applicable to future CTCS consideration were:

- Pedestrian Warning Systems- This case study looks at the Greater Cleveland Regional Transit Authority's (RTA) use of pedestrian warning systems to prevent bus collisions that occur when they make a turn at an intersection without properly detecting a pedestrian or bicyclist in the vicinity. RTA implemented turn detection sensor in the steering column of approximately 400 buses that would create a sound warning when the turn radius of greater than 45 degrees was detected for the bus, which led to decreased incidents.
- Transit Safety Retrofit Package- In the Michigan Safety Pilot Model Demonstration in Ann Arbor, about 3,000 vehicles were supplemented with CV technologies including several Transit Buses. These applications tested warning systems that looked out for crashes or pedestrians in the vicinity using DSRC radios in an onboard unit, Global Positioning System (GPS), and Crosswalk Motion Sensors.
- Connected Intersections and Mobile Apps in New York City- As part of AT&T's Connected Intersections challenge, the city of New York hosted this challenge to see how mobile technology could be used to increase safety for pedestrians. The first prize winner was an app that used Bluetooth to communicate with crosswalk signs to provide warnings to pedestrians at intersections.

KEY OUTCOMES

Key outcomes of this research are:

- Pedestrian Warning Systems- As RTA and other agencies have found in their implementation of the warning system, one of the biggest issues is cost at $1,500 to $2,500 per vehicle. In addition, the technology is limited in that it's difficult to find a perfect medium where the warning is audible but not

[14] https://rosap.ntl.bts.gov/view/dot/32380

too loud, and the sensors are hard to calibrate, which can lead to false warnings. Ultimately, while the technology may work in some cases, the effectiveness varied based on the environment since it may blend in with louder, urban settings. Intersection based detection however would only need to be installed at the intersection and leverage the CV investment that is occurring.

- Transit Safety Retrofit Package- Similar to the Pedestrian Warning System, this project focused on conveying pedestrian presence to bus drivers. Testing yielded a high number of false alerts due to limitations from the GPS and detector devices and showed that more accurate detection, and more precise location tracking technology would have to be implemented, such as differential GPS. In line with PED-SIG, multiple ways to reliably detect and notify drivers of pedestrians would be beneficial for redundancy and enhanced safety.
- Connected Intersections and Mobile Apps in New York City- One of the issues with implementing this app effectively is the feasibility of setting up receptive equipment at intersections throughout the city and the need for a high market penetration for the app to be useful. It did however show that there is a market for apps on phones to address this safety issue.

2.2.2 DEVELOPMENT AND FIELD TESTING OF AN INTERACTIVE TRANSIT STATION INFORMATION SYSTEM (ITSIS) USING CONNECTED VEHICLE TECHNOLOGIES[15]

RESEARCH OVERVIEW

This 2017 research conducted by PATH for CalTrans investigates interactive transit station information systems and their use to help make transit more appealing for travelers using CV technologies. By creating a real-time transit traveler information system that allows users to see updates via the internet and personal mobile devices, the researchers aimed to further improve the experience and convenience for riders. The research identifies three technical gaps inhibiting the development of ITSIS, which include limited coverage, low update rates, and lack of personalized information. Using surveys, they could capture rider feedback after experiencing an ITSIS prototype at two transit stops. The survey questioned topics such as wait time, bus location, stop requests, and transfer information.

RELEVANCE TO CTCS RESEARCH

As part of the research, this project offers the opportunity to analyze the application of CV technologies that CTCS is also interested in, such as if DSRC can improve the quality of real-time data, if including multi-modal data will affect ride decision making, and how ITSIS can be used for enabling real-time dynamic transit operations, amongst other related topics.

KEY OUTCOMES

Key outcomes of this research are:

- More than 70% of surveyed passengers found all the ITSIS functions to be rated at least important, with the exception of the map function.
- 35.2% of surveyed passengers felt that ITSIS would make them ride the bus more frequently.

[15] http://www.dot.ca.gov/newtech/researchreports/reports/2018/CA18-2521_FinalReport.pdf

2.2.3 IMPROVING THE SAFETY AND MOBILITY OF VULNERABLE ROAD USERS THROUGH ITS APPLICATION (VRUITS)[16]

RESEARCH OVERVIEW

The Intelligent Transport Systems (ITS) Vulnerable Road Users (VRU) project also known as VRUITS, was commissioned in 2013 under the FP-7 TRANSPORT Programme under the European Commission. VRUITS assessed the safety and mobility impacts of ITS applications for VRU. Advances in communication technologies allow the communication between different road users for safety applications. Research and development has mainly been concentrated on communication between cars, but also vulnerable road users should be included to improve their safety. High-positioning accuracy is required.

RELEVANCE TO CTCS RESEARCH

VRUITs heavily focuses on the needs of VRU in a CV environment, and thus plays well into the CTCS use case that handles pedestrians, bicyclists and transit users (while not inside of a transit vehicle). While VRUITS handles both safety and mobility needs of VRU, it is expected that VRUITS applications that are mobility related are going to be more applicable to use cases that are developed for CTCS. However, many of the VRUIT use cases rely on the use of a mobile device to enable its applications, and the ability of the mobile device to accurately position itself in the transportation environment will play a significant role in enabling certain applications.

KEY OUTCOMES

- Intelligent Pedestrian Traffic Signal
  - Pedestrian can activate green light demand via their smartphone and a traffic light controller provides information to the VRU via Infrastructure-to-VRU (I2VRU) communication on time-to-wait, pedestrian green times etc. The Traffic Light Controller (TLC) can extend the pedestrian green phase for safety crossing, based on the user-specific profile of the pedestrian.
  - A special focus on safety for pedestrians during allowed right turns. It warns the driver of the pedestrians' presence on crossings where the car has no visibility. A roadside sensor system, part of the TLC, detects the pedestrian and warns the driver.
  - Provides real-time information (based on roadside detection) to the Traffic Signal regarding the number of pedestrians waiting to cross, and their average speed; the Traffic Signal extends the pedestrian green phase based on their speed and how many people are waiting to cross.
- Intersection Safety for VRUs
  - For left- and right-turn assistance, a roadside infrastructure detects the VRU and communicates this to the car which is turning right or left into the path of the VRU. The car driver is informed via a warning or the car automatically brakes, depending on the urgency of the situation. The roadside infrastructure also informs the VRU of a dangerous situation by e.g. flashing lights and / or making a sound.
  - For traffic signal assistance or right-of-way assistance the roadside system at the intersection can detect a dangerous situation related to violation of red light or right-of-way by either VRU or car. In this scenario, the car drives perpendicular to the path of the VRU. The roadside infrastructure detects the VRU crossing the intersection. The roadside system informs the car

[16] https://cordis.europa.eu/project/rcn/186986/brief/en

about the presence of the VRU. The roadside system can also inform the VRU (via flashing lights/ sound) about the presence of the on-coming car.

  - The above two sub-cases could also be supported through a vehicle detecting a pedestrian and forwarding this information to other vehicles to support the use case.

- VRU presence warning via a VRU Beacon
  - The VRU carries a simple device (e.g. smartphone, or wearable tag in bags or clothes) that detects the presence and localizes the VRU by the roadside infrastructure or in-vehicle systems. The signal sent by the VRU device can be detected by a device installed in cars. The roadside or car is equipped with a VRU localization unit, to detect the presence or track the VRU.
- VRU presence warning via Roadside Pedestrian Presence
  - The system detects that a pedestrian is near the roadside, close to a crossing or bus stop and warns upcoming motorized traffic with flashing lights or information on a display. The pedestrian is either detected through a beacon, worn by the pedestrian (cooperative version), or by infrastructure sensors (standalone version).
- VRU warning via Bicycle-to-Car Communication
  - The exchange of information between bicycles and cars can be enabled. By sharing their position and dynamics using wireless communication, cyclist and car driver can both be warned to avoid the collision.
- VRU warning via Pedestrian-to-Car Communication
  - As for the Bicycle-to-Car and the Powered Two Wheel (PTW)-to-Car communications, also Pedestrians can have a device, allowing receiving and transmitting information. A smartphone application allows pedestrians to transmit their status (position, and possibly other sensors), which can be received by Road Side Units and cars. The device has intelligence to process incoming messages from cars and infrastructure, and to warn pedestrians in case of collisions.
- Road Safety via Powered-Two-Wheel Oncoming Vehicle Info System
  - This system is used on a PTW to warn the PTW driver on oncoming cars. This system is different from the car-based systems, since the PTW is equipped with a system that processes its internal sensor information and fuses it with external cooperative information to determine a possible collision risk.
- VRU warning via Cooperative VRU Detection
  - Information on unequipped pedestrians, bicyclists or PTW are forwarded to other cars. Information is relayed by cars or infrastructure to all cars within the range of interest. Example cases are VRUs at highways (e.g. person leaving a breakdown car), pedestrians walking along rural roads in low visibility circumstances, or pedestrians crossing a road after a sharp turn.
- Green Wave for Cyclists
  - Cyclists receive a speed advice; if they follow it, they are guaranteed a green light at the next controlled intersection.
    - Version 1: the speed advice is provided from the roadside, either via one or more dynamic roadside signs, or via moving led lights along the road.
    - Version 2: the speed advice is provided via a personal device (a smartphone or a bicycle computer).
- Human presence on the road

- This is intended to be used only to send a warning in a road environment normally forbidden to pedestrians (such as a freeway) or where pedestrians are not expected (such as a rural road).

2.2.4 SHARING DATA BETWEEN MOBILE DEVICES, CONNECTED VEHICLES AND INFRASTRUCTURE[17]

RESEARCH OVERVIEW

This USDOT research project, performed by Battelle, starting in 2015, studied the impact and effectivity of the use of mobile devices in a CV environment by designing, developing, prototyping and testing personal safety and personal mobility messages, exchanged between human-carried devices and vehicles, or with other humans similarly equipped, in a series of controlled tests. Referenced is the final Field Test, Evaluation Plan and Result document. A complete set of documents may be found on the National Transportation Library. The resulting prototype was designated the D2X-Hub, a name that borrows from the similar functionality found in the V2I Hub, but with an emphasis on the device portion.

RELEVANCE TO CTCS RESEARCH

The results of the limited prototype do show, that similar to earlier MMITSS findings for PED-SIG, mobile devices can be used to interact with a reasonable level of confidence in a CV environment. The resulting messages, the personal safety message (PSM) and personal mobility message (PMM) also demonstrated that the breadth of data needed to support these interactions are available. From the CTCS perspective, a need exists to determine if/how signalized intersections could use the PSM (now part of SAE J2735:2016) and the PMM, which is yet to be standardized, to affect signal timing.

KEY OUTCOMES

- PSM was added to J2735 in part due to the research performed under this contract.
- PMM use demonstrated an ability to reduce demand on number of active dialogs between CV-enabled devices by introducing the concept of traveler groups for VRUs.

2.2.5 CONNECTED VEHICLE PILOT DEPLOYMENT PROGRAM PHASE 1, APPLICATION DEPLOYMENT – TAMPA HILLSBOROUGH EXPRESSWAY (THEA)[18]

RESEARCH OVERVIEW

In September 2015, the Tampa Hillsborough Expressway Authority (THEA) and a group of regional partners were selected as one of three cities to be awarded USDOT's CV Pilot Deployment Program. As part of this deployment program, applications for urban congestion and wrong way driving (due to the express lane being reversible during certain times) were investigated. To facilitate this research, the organization created the region-wide Connected Vehicle Task Force and deployed DSRC to enable transmission between approximately 1,600 cars, 10 buses, 10 trolleys, 500 pedestrians with the smartphone applications, and approximately 40 roadside units.

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[17] https://rosap.ntl.bts.gov/view/dot/32869
[18] https://rosap.ntl.bts.gov/view/dot/31734

RELEVANCE TO CTCS RESEARCH

This project is an example of the MMITSS concepts applied in a real-world environment outside of the original research context. The following MMITSS applications are being deployed as part of the THEA CV Pilot:

- Intelligent Traffic Signal System (I-SIG)- This application uses vehicle location and movement information from CVs as well as infrastructure measurement from non-equipped vehicles to optimize signal timing based on the approaching vehicles.
- Transit Signal Priority (TSP)- This application allows certain transit vehicles to request priority at the intersection

KEY OUTCOMES

At the time of this report, I-SIG was still being tested in real-world test beds, while TSP is still in the conceptual stages and being tested under simulated conditions. Although the technology is expected to achieve benefits such as reduced travel times, and increased transit priority, it is evident that the testing phases will need to be studied and analyzed before they can be considered viable in real world situations.

2.2.6 *PERFORMANCE MEASUREMENT EVALUATION FRAMEWORK AND CO-BENEFIT TRADEOFF ANALYSIS FOR CONNECTED AND AUTOMATED VEHICLES (CAV) APPLICATIONS: A SURVEY*[19]

RESEARCH OVERVIEW

This 2017 study conducted by the National Center for Sustainable Transportation (NCST), as sponsored by USDOT's University Transportation Centers (UTC) program, analyzes the measures of effectiveness (MOEs) on recent CAV applications, and concludes with the identification of influential factors on system performance, and suggested approaches for obtaining co-benefits across different types of MOEs. By breaking down CAV applications into three categories (vehicle-centric, infrastructure-centric, and traveler-centric applications), they can then be analyzed and compared by their respective MOEs. Researchers found that currently there are very few applications that are designed to collectively impact safety, mobility, and environmental impacts directly, although they may have indirect effects that touch on all the topics, with safety being the main targeted benefit. Moreover, the research found that there are some applications which may negatively impact other categories. Unfortunately, there are currently very few studies which review all three types of MOEs and how they impact each other either positively and negatively.

RELEVANCE TO CTCS RESEARCH

As part of this research, researchers investigated applications relevant to CTCS including automated on-ramp merging, and eco-friendly freight signal priority system. While automated on-ramp merging benefits safety and mobility, applications like eco-friendly freight signal priority benefit mobility and environmental impacts. For on-ramp merging, the study team leveraged previous experiments which used a fuzzy algorithm combined with a distance reference system to improve traffic flow and congestion. For freight signal priority, the study team considered a study which used a regulation scheme of signal timing that led to increased travel time and reduced fuel consumption. The relevance to CTCS is the need to consider the impact/balance of any of the outcomes resulting from CTCS use cases.

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[19] https://ncst.ucdavis.edu/wp-content/uploads/2017/09/NCST_Qi-UCR_Perf-Measurement-Eval-Framework-and-Co-Benefits-Tradeoff-Analysis-for-CAV-Apps_Final-Report_SEPT-2017.pdf

KEY OUTCOMES

Key outcomes of this research are:

- Factors that contribute to improved system performance including better trajectory planning, increased spacing, capacity increase, speeds/deceleration smoothing, regenerative braking, and vehicle's dynamics and exogenous signal phase and timing adjustment, the latter of which is a function of CTCS.
- Penetration rate of applications needs to be considered in future studies since applications may have variable effectiveness based on this parameter.

2.3 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 could leverage vehicle-to-vehicle (V2V) communications to enable vehicle platooning but also vehicle-to-infrastructure (V2I) communications to communicate the arrival of vehicle platoons to intelligent transportation system (ITS) field equipment – mainly traffic signal controllers.

2.3.1 TRANSPORTATION PLANNING IMPLICATIONS OF AUTOMATED/CONNECTED VEHICLES ON TEXAS HIGHWAYS[20]

RESEARCH OVERVIEW

This 2017 report prepared by Texas A&M Transportation Institute for TxDOT and FHWA suggests that transportation planning will face challenges with not being able to use historical data to predict and model future traffic conditions once CAV are widespread. Regardless, CAVs will help planners achieve goals established by MAP-21, such as safety, congestion, system reliability, and environmental sustainability, and change how the public perceives them. For example, if drivers can use time spent in an autonomous car productively, congestion would not be as negatively perceived. Thus, planning goals may shift to address the needs of passengers having the ability to make the most of their productivity time, and less about drastically reducing travel times.

RELEVANCE TO CTCS RESEARCH

This report examines transportation planning based on implementing CAV technology and breaks down current and emerging technologies involving CAV, including adaptive cruise control, cooperative cruise control, and potential ramp metering applications.

Even though most commercially available vehicles are only at automation level 1 and 2, there are barriers moving forward for more advanced automation that inhibit CAV applications. These include:

- Normalizing different data sources
- Limited and unreliable GPS information

[20] https://rosap.ntl.bts.gov/view/dot/32218

- Accuracy of sensors
- Dealing with extreme driving conditions

In addition, without a significant inclusion of CAVs within the overall vehicle fleet already publicly deployed, there is limited data available for transportation planners to use to build models. Thus, moving forward, as CAVs become more familiar to the public, all stakeholders will need to monitor how CAVs are perceived and work together to uniformly develop the policies, technology, and data needs involved, based on a maturing understanding of the technology and the effectiveness of its applications.

KEY OUTCOMES

Key outcomes of this research are:

- Early on, stakeholders must transparently show the capacity impacts/ potential of CAV applications
- New technologies and tools will need to be created concurrently with the deployment and development of CAV
- Regional modeling and simulation will need to be used

2.3.2 AN ASSESSMENT OF AUTONOMOUS VEHICLES: TRAFFIC IMPACTS AND INFRASTRUCTURE NEEDS: FINAL REPORT[21]

RESEARCH OVERVIEW

This University of Texas – Austin report for TxDOT, published in 2017, examines the current state of AV and CV technologies as well as the public's perception of them. While the consensus is that advanced automated technologies are not yet mainstream, it did find that there are performance improvement metrics that can be realized through utilizing the technology. For example, automated ramp metering and DSRC communication led to a reduction in congestion delays in merging areas from 7% to 16%. These results were based off flow and travel demand link-based mesoscopic (mid-scale) models.

RELEVANCE TO CTCS RESEARCH

The University of Texas at Austin Center for Transportation Research conducted a cost-benefit analysis to better understand how connected and automated vehicles will impact drivers while considering multiple market penetration rates and low levels of technologies. The impact to CTCS is the evidence that expanding MMITSS beyond single signalized intersections to include ramps could have a positive benefit to future AVs.

KEY OUTCOMES

Key outcomes of this research are:

- With market penetration rates of 10%, 50%, and 90%, it was determined that CAVs will create a net present value of $13,960, $22,024, and $27,000 respectively per vehicle's life time.
- In the state of Texas, the most interesting level 1 technology were blind-spot monitoring and emergency automated braking, which had 59.9% and 56.9% adoption rate, respectively.

[21] https://rosap.ntl.bts.gov/view/dot/31990

2.3.3 INTEGRATING EMERGING DATA SOURCES INTO OPERATIONAL PRACTICE[22]

RESEARCH OVERVIEW

This 2017 report prepared for FHWA by Kimley-Horn, discusses that as connected and automated vehicles become more integrated in society and require more and more data to be processed, there will inevitably be a need to address the way in which this data is handled, how the data can satisfy current and future traffic management system needs, and what needs may arise in the future to mitigate data communication.

RELEVANCE TO CTCS RESEARCH

For agency RSE and systems to advance with CAVs, there will be a need for them to integrate and utilize more data. Currently, a lot of agencies take data sourced from RSUs like loop detectors, often on a once per second basis, and average it over a short period to produce a pseudo-live feed report on the traffic conditions. However, as other stakeholders develop their technology to more efficiently record data at faster rates, agencies in turn will need to restructure their data recording processes and frameworks. Furthermore, current RSE is inept in processing and communicating CV data through different data aggregation strategies.

KEY OUTCOMES

Key outcomes of this research are:

- RSE will need to be able to differentiate relevant data since data from adjacent roads will be mixed in. Thus, proper geofencing strategies need to be in place.
- Data compression will be needed for offline applications
- RSE will need to be able to process multiple formats of electronic messages
- Existing traffic management industry practices are not adequate for sharing CV data from hundreds of RSE and instead need to invest in Big Data applications

2.3.4 MANAGING AUTOMATED VEHICLES ENHANCES NETWORK (MAVEN)

RESEARCH OVERVIEW

The Managing Automated Vehicles Enhances Network (MAVEN) project is funded by the European Commission under Horizon 2020 Research and Innovation Framework Program. [23] MAVEN aims to provide solutions for managing automated vehicles in an urban environment (with signalized intersections and mixed traffic). It will develop algorithms for organizing the flow of infrastructure-assisted automated vehicles and structuring the negotiation processes between vehicles and the infrastructure. The MAVEN approach will substantially contribute to increasing traffic efficiency, improving utilization of infrastructure capacity, and reducing emission. [24]

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[22] https://transportationops.org/publications/integrating-emerging-data-sources-operational-practice
[23] http://www.maven-its.eu/
[24] http://adas.cvc.uab.es/maven/wp-content/uploads/sites/16/2018/06/MAVEN-C2C-CC_2.pdf

RELEVANCE TO CTCS

MAVEN focuses on coordination of AVs. However, there are use cases in the CTCS project that may include vehicles that are in automated platoons (i.e. forward control, at a minimum), driver-controlled vehicles that are coordinated in a platoon, and non-automated non-platooning CVs. The same principles could be applied in the CTCS project.

There are portions of the I2V Interactions and traffic light controller optimization MAVEN use cases that could apply to the CTCS arterial traffic control use case. Vehicles broadcasting their location could be captured by equipment at an intersection. Equipment on the roadside at the intersection could receive messages from all vehicles approaching the intersection to determine how to best serve the approaching traffic. It could provide increased priority for movements with more approaching vehicles, or to give priority to a platoon of approaching vehicles.

The Platoon Management MAVEN use case could play an important role in the Level 1 longitudinal control CTCS use case, as it provides a means of facilitating the formation of a platoon that could improve the efficiency of traffic movement along a corridor.

Traditionally, vehicles/pedestrians are detected through roadside ITS equipment or by carrying an in-vehicle/mobile device that broadcasts the vehicle's/pedestrian's location or intent information. Because there are no CTCS use cases that explicitly handle the automated detection of objects, it is anticipated that there is limited transferability of the Inclusion of Conventional Traffic and VRUs use case to CTCS use cases. However, it is possible that an automated vehicle could detect other vehicles and VRUs – information about these detected objects could be broadcast by the detecting vehicle via CV technology to enhance CTCS use cases that rely on knowledge of the location and motion information of vehicles and/or VRUs.

KEY OUTCOMES

MAVEN use cases include:

- I2V interactions.
  - V2I "explicit" probing - CAVs and/or platoons transmit planned route, desired speed, platoon size, etc. Information needs include the CAV route at intersection, distance to preceding/following vehicle, platoon id, platoon participants, and desired platoon speed.
  - Traffic light controller signal timing re-optimization and I2V advisories - Based on Rx information/calculations, infrastructure transmits GLOSA and Lane Advisory Message (LAM). Information needs include suggested speed for a given lane (calculated based on queue estimation), signal timing information, intersection geometry information, suggestions on the lane a CAV should change to at an intersection, distance to stop line, and time for starting maneuver.
  - V2I feedback on compliance to advisories - CAVs and/or platoons communicate if suggestions can be executed. If yes, traffic light controller "freezes" signal timing optimization. Information needs include acknowledgement on whether the GLOSA and/or LAM are being executed by the CAV.
- Traffic light controller optimization, such as signal optimization, priority management, queue estimation, or a green wave.
  - Platoon management. Forming, joining, travelling in, leaving, or breaking a platoon or string.
  - Based on common distributed algorithm and V2V exchanged info, individual vehicles form platoons or strings and manage their operation (joining, leaving, etc.).
  - The platoon or string leader has the central role of communicating platoon or string features to the infrastructure for explicit traffic probing.

- Two channels are used – one to advertise vehicle and/or platoon and/or string characteristics to other vehicles or infrastructure, and another to convey more frequent platoon or string control and management information.
- Platoon Initialization Message includes information that contains information for joining a platoon or string including but not limited to expected route, desired speed, etc.

- Inclusion of conventional traffic and VRUs – detection/reaction in presence of non-cooperating cars & VRUs.
  - Both CAVs and infrastructure can detect and share information about non-cooperative road users
  - Improved awareness used to adapt CAV maneuver/path planning for increased safety
  - Isolated CAVs or CAVs in platoon keep monitoring the environment and control the system all the time to possibly undertake emergency (automated) reactions

2.3.5 STRATEGIC INNOVATION PROMOTION PROGRAM (SIP) AUTOMATED DRIVING FOR UNIVERSAL SERVICES (ADUS) ACTIVITIES

RESEARCH OVERVIEW

Cross-ministerial Strategic Innovation Promotion Program (SIP) automated driving for universal services (ADUS) is an initiative from Japan that is undertaking activities with the objective of solving issues of concern today, including reducing traffic accident fatalities and traffic congestion, along with securing transportation methods for the elderly and others with limited mobility.[25] [26]

RELEVANCE TO CTCS RESEARCH

The SIP-ADUS primarily focuses on the use of wirelessly transmitted messages to improve the awareness of automated vehicles to their surroundings. This primarily has implications for the Level 1 longitudinal control use case.

KEY OUTCOMES

SIP-ADUS use cases of automated driving using cooperative ITS:

- Look-Ahead information from the road - Information ahead that cannot be detected using autonomous sensors is acquired through the road infrastructures, realizing smooth automated driving
- Emergency Hazard information from vehicles - Information on hazards, such as road obstacles, is gathered from the automated vehicle and sent to following vehicles
- Merging/lane change assist information - By acquiring information on nearby vehicles when merging, and exchanging control intentions among vehicles involved in the merge, to realize safe and smooth automated merging

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[25] https://connectedautomateddriving.eu/wp-content/uploads/2017/08/2017-06-19_Uchimura_SIS04-SIP-adus.pdf
[26] http://en.sip-adus.go.jp/wp/wp-content/uploads/e09_itsforum2018_s.pdf

- Vehicle platooning - Automated control information is mutually exchanged among platooning vehicles, realizing vehicle platooning

2.3.6 AUTOPILOT

RESEARCH OVERVIEW

Automated Driving Progressed by Internet of Things (AUTOPILOT) is one of the European Commission's Large-Scale Pilots (LSPs), specifically Pilot 5: AV in a connected environment. The overall objective of the AUTOPILOT project is to enable safer highly automated driving thanks to smart and connected objects and the Internet of Things.[27]

RELEVANCE TO CTCS RESEARCH

The platooning use case for the AUTOPILOT project could be applicable to the CTCS Level 1 longitudinal control use case. V2V communications could be used to form and maintain a platoon of automated vehicles on an arterial roadway network to improve efficiency. The ability to detect road hazards using data from vehicles could be used in the lane management use case to make approaching drivers aware of the hazard, potentially improving efficiency. While the Automated Driving Route Optimization AUTODRIVE use case focus on routing drivers to parking spaces, the same logic could be applied to efficiently routing drivers along arterials to a freeway access point to support the arterial traffic control CTCS use case. Finally, there are aspects of the Vulnerable Road User Sensing use case that could be applied to the CTCS use case that handles pedestrians and bicyclists. However, Vulnerable Road User sensing predominately focuses on pedestrian safety, whereas the CTCS will likely primarily focus on the mobility of pedestrians.

KEY OUTCOMES

The AUTOPILOT project will deploy, test and demonstrate Internet of Things (IoT)-based automated services in five driving modes - urban driving, highway pilot, automated valet parking, real time car sharing, and platooning - at several permanent pilot sites, in real traffic situations. Furthermore, the AUTOPILOT project will create and deploy new business products and services for fully automated driving vehicles.

- Platooning (Driving Modes) - The platooning use case demonstrates vehicular platoons consisting of a lead vehicle and one or more highly automated or driverless following vehicles which have automated steering and distance control to the vehicle ahead. The control is supported by V2V communication. Two variants of platooning will be evaluated in the project:
    - An urban variant to enable car rebalancing of a group of driverless vehicles involving only one driver in the lead vehicle
    - A highway variant where one or more highly automated vehicles are going to follow a leading vehicle. The electronic allowance of the emergency lane (dedicated lane) will be tested, as well as dynamic platoon forming
- Highway Pilot (Driving Modes) - In the Highway Pilot use case, a cloud service merges the sensors' measurements from different IoT devices to locate and characterize road hazards. The goal is then to provide the following vehicles with meaningful warnings and adequate driving recommendations to manage the hazards in a safer or more pleasant way.
- Automated Driving Route Optimization (Driving Services) - The AUTOPILOT IoT service platform monitors vehicles and their environment to optimize automated driving routes of autonomous driving

[27] http://autopilot-project.eu/

cars, by redistributing the traffic along alternative paths towards available parking spots. The relevant data tracked includes, for instance, the real traffic conditions, weather conditions, events, and available parking spots at the destination. This service is likely to contribute to predicting traffic for automated driving car sharing.

- Vulnerable Road User Sensing (Driving Services) - One of the biggest challenges autonomous cars must face in urban scenarios, is the number of unexpected events which may occur suddenly such as a pedestrian or cyclist crossing the street. IoT services can give information about these vulnerable road users by connecting to the smart devices they are wearing (smartphones, smart watches, smart glasses).

2.4 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).

2.4.1 ESTIMATED BENEFITS OF CONNECTED VEHICLE APPLICATIONS: DYNAMIC MOBILITY APPLICATIONS, AERIS, V2I SAFETY, AND ROAD WEATHER MANAGEMENT APPLICATIONS[28]

RESEARCH OVERVIEW

This 2015 report prepared by Nobles analyzes four USDOT sponsored V2I research programs (V2I Safety, DMA, AERIS, and Road-Weather Management), and discusses the impacts that can result from them. For example, the Eco-friendly Integrated Corridor Management (ECO-ICM) Operational Scenario application considers how CV and other future technologies may support the integrated operation of a major travel corridor to reduce transportation-related emissions on arterials and freeways, while also considering environmental and performance-based metrics. This can then be used to help agencies make operational decisions later. However, it is important to note that the application led to different results based on the pioneer site. Other applications such as eco-ramp metering and adaptive cruise control were also tested and shown to lead to improved travel times on freeways and performance.

RELEVANCE TO CTCS RESEARCH

The AERIS program investigates how ECO-ICM Operational Scenario builds on past ICM initiatives to also consider operations that will reduce emissions through tracking environmental data and performance metrics. ECO-ICM is enabled by means of a series of strategies which include reporting of current and next signal phases and adaptive signal control, both features that CTCS might consider.

[28] https://rosap.ntl.bts.gov/view/dot/3569

KEY OUTCOMES

Eco-ICM, when analyzed in San Diego, CA suggests that vehicles could achieve:

- 246,000 hours of annual travel time savings
- 323,000 gallons of fuel saved annually
- 3,100 tons of mobile emissions saved
- Benefit-Cost Ratio of 10:1

In Dallas, TX, benefits were determined to be:

- 740,000 hours of annual travel time savings
- 981,000 gallons of fuel saved annually
- 9,400 tons of mobile emissions saved
- Benefit-Cost Ratio of 20:1.

2.4.2 LEVERAGING THE PROMISE OF CONNECTED AND AUTONOMOUS VEHICLES TO IMPROVE INTEGRATED CORRIDOR MANAGEMENT AND OPERATIONS: A PRIMER[29]

RESEARCH OVERVIEW

This primer, produced in 2017 by Leidos and DKS Associates for USDOT provides an introduction of CAV and how it can be implemented for ICM by looking at the institutional, operational, and technical aspects of ICM. By looking at it as a symbiotic relationship, the report goes on to see how both ICM and CAV can address challenges and help each other.

RELEVANCE TO CTCS RESEARCH

ICM employs several different strategies to improve safety, mobility, and environmental conditions for vehicles traveling along its corridor, which can all be improved upon through CAV. ICM operators and planners are seeing a shift in how operations are being conducted, such as in data management and storage and the employment of new technologies and RSE. Moreover, with the inevitable market penetration of CAV, ICM stakeholders must embrace and work with CAV stakeholders to ensure safety of users of the corridor, fluid traffic, and most importantly be open to new changes. CTCS is a conduit for the two-way exchange of data with vehicles to support ICM strategies.

KEY OUTCOMES

- CAV provides a new source of real-time data that can be used for more accurate historical and predictive modeling for ICM.
- Ultimately with the introduction of full AVs, it will lead to some RSE being redundant or outdated and no longer needed, which can help save costs for building ICM implementation infrastructure.

[29] https://ops.fhwa.dot.gov/publications/fhwahop17001/fhwahop17001.pdf

- Using CAVs on corridors provides a source of corridor condition data for vehicle manufacturers and original equipment manufacturers (OEM) to use that was previously not widely available.

2.4.3 REPORT ON DYNAMIC SPEED HARMONIZATION AND QUEUE WARNING ALGORITHM DESIGN[30]

RESEARCH OVERVIEW

This 2014 report produced by TTI for USDOT considers the algorithms used for speed harmonization and queue warning and the limitations and requirements that they face as traffic management applications. Using data sourced from communication between CVs and infrastructure RSE, previous algorithms can be improved. In addition, the research also discusses the formatting requirements for INFLO due to the nature of this new data.

RELEVANCE TO CTCS RESEARCH

CV technologies create a new source of data that can be implemented with speed harmonization and queue warning systems to create dynamic, real time systems. Relevant to CTCS, this research aims to detect when and where congestion comes from, to create accurate speed recommendations and warnings, and to communicate this information far enough in the traffic stream for it to be effective. The queue warning and speed harmonization process involves looking at the corridor at the link level across the lanes for congestion and then at the lane level. Based on these results, the recommendations are then sent to the appropriate drivers using V2I and V2V technologies.

KEY OUTCOMES

Speed Harmonization/ Queue Warning System- This system analyzes data from CVs, infrastructure weather and traffic sensors, and mobile weather monitoring systems and processes it such that the algorithm can interpret it. Through the algorithm, this application system can be used to disseminate appropriate speed recommendations and warnings to vehicles approaching congestion.

2.4.4 COOPERATIVE INTELLIGENT TRANSPORTATION SYSTEMS PLATFORM PHASE 2[31]

RESEARCH OVERVIEW

Convergence between cooperative, connected and automated systems is expected to bring several benefits in terms of road safety, traffic flow efficiency and emission reduction.

RELEVANCE TO CTCS RESEARCH

The outcomes of this project related to CTCS are predominately associated with the CV ICM use case. It provides building blocks for digital traffic management plans, like methodologies for ICM projects in the United States, for determining when to tell drivers to take an alternative route.

[30] https://rosap.ntl.bts.gov/view/dot/3534
[31] https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf

KEY OUTCOMES

- Classification of roads allows traffic managers to indicate road network hierarchy and preferred routes. Can be used for rerouting traffic around a congested area or for activating a green light optimized speed advisory
- Geofencing mechanism – translates urban planning to prevent routing through residential areas or close to hospitals or schools.
- Establishing a network level of performance based on performance indicators (such as speed and volume) derived from data collected from loops or probe vehicle CV data
- Trigger - the point in which the acknowledgment of data turns into action

2.5 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, allow use of shoulders as temporary travel lanes, and/or prohibit or restrict types of vehicles from using particular lanes.

2.5.1 *REAL-TIME TRAFFIC MANAGEMENT TO MAXIMIZE THROUGHPUT OF AUTOMATED VEHICLES*[32]

RESEARCH OVERVIEW

This March 2015 report produced by the Mountain-Plains Consortium, a USDOT-sponsored UTC, investigates how to create a strategy to achieve successful lane changes through AVs since there are no current studies to the institution's knowledge that maximizes the number of lane changes for live traffic on a stretch of a highway with an arbitrary number of lanes. Thus, the report goes into designing an algorithm that maximizes the number of possible lane changes on an arbitrary segment of a highway at any given time using metrics like vehicle position and speed. The algorithm is tested through several simulations where the parameters can be changed based on the criteria.

RELEVANCE TO CTCS RESEARCH

With the introduction of AVs, there is a need to see how they can fluidly interact with other vehicles while traveling in and out of corridors. This involves lane changing without creating delays/ incidents with human drivers. The CTCS concept can take this further by providing guidance to AVs with respect to recommended or restricted lanes.

KEY OUTCOMES

Key outcomes of this research are:

[32] https://rosap.ntl.bts.gov/view/dot/28783

- Using the time algorithm proposed in this study, it has been shown that AVs can successfully be integrated with manual vehicles since it showed a significant increase in the number of lane changes compared to current baseline algorithms.
- A priority scheme must be developed to allow AVs to know what vehicle can change lanes to exit.
- Acceleration needs to be investigated more to maximize lane changes
- There needs to be more research conducted on the autonomy behind whether an AV should change lanes.

2.5.2 DYNAMIC LANE REVERSAL ROUTING AND SCHEDULING FOR CONNECTED AUTONOMOUS VEHICLES[33]

RESEARCH OVERVIEW

This 2017 study published by the University of Hong Kong tests to see whether dynamic lane reversal in conjunction with the use of CAV can improve the capacity of congested roads. Although current applications of dynamic lane reversal are usually during set peak hours for certain traffic patterns, CAV provides the opportunity for transportation planners to more actively react to current traffic patterns and employ these applications more effectively. One of the drawbacks that CAV addresses is the confusion of human drivers when lanes are suddenly changed in direction. By applying lane reversal too frequently, this can lead to higher rates of accidents between vehicles since it takes humans time to be aware of what's occurring and to adapt properly. However, with CAVs, this programming is automatically incorporated into their routing plans so there is a smaller likelihood of incidents to occur.

RELEVANCE TO CTCS RESEARCH

Dynamic Lane Reversal (DLR) is particularly useful in the context of CAVs since they can communicate with the infrastructure and with other vehicles through V2V and V2I technologies to receive lane direction, signal priority, and other information. Moreover, because they use electronic messaging that is much faster than humans can react, CAVs can more efficiently deal with dynamic changes in traffic flow. CTCS could be used to provide both lane control and signal control in situations of reversed lanes.

KEY OUTCOMES

Key outcomes of this research are:

- One thing to consider in the future with the introduction of CAV is how mixed fleets of CAVs and human operated vehicles will deal with DLR.
- Traffic Scheduling Management (TSM) is helpful in reducing the travel time by appropriately planning the departure times of CAVs so that they are not stuck at traffic points.
    - Without TSM, these vehicles would depart at their earliest possible departure times and exacerbate the already bad traffic jams.
- Scalability will need to be investigated with these types of theoretical research applications.

[33] https://ieeexplore.ieee.org/abstract/document/8090813

2.5.3 FREEWAY LANE MANAGEMENT APPROACH IN MIXED TRAFFIC ENVIRONMENT WITH CONNECTED AUTONOMOUS VEHICLES[34]

RESEARCH OVERVIEW

This paper, published by University of South Florida, proposes a model for mixed traffic corridors composed of CAVs and human operated vehicles to figure out the maximum number of vehicles. The model investigates how single-line operations compares to managed lanes with respect to different penetration levels of CAV technologies being applied to figure out the optimal number of dedicated lanes for CAVs.

RELEVANCE TO CTCS RESEARCH

This research builds upon past research and application of managed lanes to further use it to separate CAVs from mixed traffic to take advantage of the operational benefits that CAVs have when operating together. For example, this includes V2V communication to create optimal headway gaps, speed optimization, etc. The analytical model developed in this research is used to figure out the optimal number of CAV-only lanes needed for a freeway.

From the literature review they conducted, they found that strategies that control automated vehicle speeds, such as proposed trajectory control and variable speed limit control, all had beneficial impacts on traffic efficiency and sustainability. Additionally, these studies looked at creating dedicated CAV lanes with defined boundaries on how they would operate, but very few studies looked at the optimal number of lanes for the performance of mixed traffic. Thus, to do this, they assume CAVs and human drivers are randomly distributed and defined four different types of headways and freeway total throughput based on the CAV penetration rates.

KEY OUTCOMES

Key outcomes of this research are:

- For single-lane problems, as CAV penetration rates increase, freeway capacity increases also.
- For managed lane problems, more aggressive and advanced CAV technologies can use fewer CAV-only lanes due to their efficiencies.
- The number of lanes needed and congestion in lanes generally decreases as CAVs utilize more advanced technologies.

2.5.4 ECO-TRAVELER INFORMATION APPLICATIONS, AFV CHARGING/FUELING INFORMATION, ECO-SMART PARKING, DYNAMIC ECO-ROUTING (LIGHT VEHICLE, TRANSIT, FREIGHT), ECO-ICM DECISION SUPPORT SYSTEM[35]

RESEARCH OVERVIEW

This research identified five operational scenarios where environmentally beneficial applications can be implemented. As stated in the title, these include Eco-Signal Operations, Eco-Lanes, Low Emissions Zones, Eco-Traveler Information, and Eco-ICM. Within each operational scenario, it is packaged with a set of applications,

[34] https://arxiv.org/ftp/arxiv/papers/1609/1609.02946.pdf
[35] https://www.its.dot.gov/research_archives/aeris/pdf/AERIS_Operational_Scenarios011014.pdf

regulations/policies, performance measures, and other tools. These tools include educational videos and campaigns to inform the public about the applications, how they work, and how they can benefit from utilizing them.

RELEVANCE TO CTCS RESEARCH

As part of AERIS's operational scenarios and applications, there are mobility benefits realized through using CV technologies that will improve corridor performance between intersections. CTCS could be enhanced to support any of these strategies.

- Eco-Signal Operations- As part of this operational scenario, AERIS employs 4 applications to improve performance before and while a vehicle approaches a signalized intersection. These include Eco-Approach and Departure at Signalized Intersections, Eco-Traffic Signal Timing, Eco-Traffic Signal Priority, and Connected Eco-Driving. Using real-time data communicated through RSE and onboard units, the traffic signals are optimized to increase performance and throughput of vehicles and vehicles are communicated optimal speeds to approach the intersections.
- Eco-Traveler Information- This operational scenario uses multimodal data to provide advanced travel information through an open data/ open source approach. It uses applications such as Dynamic Eco-Routing, Multi-Modal Traveler Information, and Connected Eco-Driving to analyze real-time traffic data from CVs already on the corridor to provide drivers beforehand recommendations on the best routes to take.
- Eco-ICM- This operational scenario investigates collaborating with the various operators on corridors to better coordinate their operations to improve efficiency. The applications applied for this use real-time data and decision support systems to decide what operational decisions will have the most environmentally friendly impact. CTCS related applications include Eco-ICM Decision Support System, which uses data from multiple sources to recommend decisions such as eco-signal timing plans, eco-ramp metering strategies, and eco-speed limits.

2.5.5 UK AUTODRIVE

RESEARCH OVERVIEW

The UK Autodrive is a consortium of leading technology and automotive businesses, forward thinking local authorities and academic institutions who are working together on a major three-year UK trial of AV and connected car technologies. The trial will culminate in a series of urban demonstrations on selected public roads and footpaths in the host cities of Milton Keynes and Coventry.[36][37]

RELEVANCE TO CTCS

In-Vehicle Signage could be implemented as part of a lane management use case. Lane management strategies are typically provided to drivers in the form of overhead signs that change depending on conditions. This same signage could be displayed in the vehicle on in-vehicle signage. If implemented correctly, this could be more informative for the driver, and it would rely less on the use of costly ITS equipment that must typically be installed.

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[36] http://www.ukautodrive.com/

[37] http://www.ukautodrive.com/uks-largest-connected-and-autonomous-vehicle-project-tackles-city-centre-parking/

The Green Light Optimal Speed Advisory is related to traffic control on arterial streets and has the potential to play a role in the longitudinal control of a vehicle.

Intersection control data can be used to provide the driver with a recommended speed with which to approach the intersection to ensure that they arrive at the intersection when the light turns green with minimal stopping. A vehicle with automated technology could adjust the speed of the vehicle to conform to the recommended speed to minimize the likelihood it must stop at the intersection to improve roadway efficiency. Interestingly, in the case that a vehicle that adheres to the recommended speed cannot be passed, all following vehicles will be constrained to that speed as well – this indicates that there could be benefits even without a high penetration.

The Intersection Priority Management application, while intended to be used with automated vehicles in UK Autodrive, could be implemented as part of an adaptive traffic signal timing plan that will likely be a component of the use case that handles arterial traffic control.

KEY OUTCOMES

Connected car features being trialed within the UK Autodrive program are:

- Emergency Vehicle Warning (EVW) – Sends a signal directly from the emergency vehicle (e.g. ambulance, fire engine, police vehicle) to nearby connected cars. Driver is informed that the emergency vehicle is approaching and advised to make way for it.
- Intersection Collision Warning (ICW) – Warns the driver when it is unsafe to enter an intersection, due to a high probability of collision with other vehicles.
- In-Vehicle Signage (IVS) – Sends information about road conditions, congestion or other incidents directly to the in-car display, rather than having to rely on expensive gantry systems.
- Electronic Emergency Brake Light (EEBL) – Alerts the driver when a vehicle in front suddenly brakes, providing advanced warning, especially when the driver is unable to see the lights of the braking vehicle due to weather conditions, road layout or other vehicles in between.
- Green Light Optimal Speed Advisory (GLOSA) – Sends traffic light information to the connected car which can calculate the optimal speed for approaching the lights, potentially minimizing the number of red light stops, improving traffic flow and reducing emission levels from idling vehicles.
- Intersection Priority Management (IPM) – Assigns priority when two or more CVs come to an intersection without priority signs or traffic lights.
- Collaborative Parking – Provides real-time information about free parking spaces either in the driver's current vicinity or close to the driver's destination.

2.5.6 COMPASS 4D

RESEARCH OVERVIEW

Compass 4D has installed equipment and implemented cooperative services on almost 300 RSUs and 600 vehicles across the European Union (EU). This deployment was spread across seven European cities: Bordeaux, Copenhagen, Helmond, Newcastle, Thessaloniki, Verona and Vigo.[38]

[38] https://www.researchgate.net/profile/Evangelos_Mitsakis/publication/267267807_Compass4D_Cooperative_Mobility_Pilot_on_Safety_and_Sustainability_

RELEVANCE TO CTCS RESEARCH

The Road Hazard Warning could be a component of the CTCS lane management use case. Hazards that are present in the roadway may warrant a lane to be temporarily closed. A traffic manager may be interested in applying a lane management strategy to improve driver awareness of the impending hazard, which has the potential to improve efficiency.

GLOSA is also related to traffic control and vehicles capable of Level 1 longitudinal control, which was discussed previously. One aspect of the GLOSA that is applied as part of the Compass 4D initiative that was not discussed in other initiatives is that the recommended speeds that are provided to drivers could be applied to corridors, not just at individual intersections. This concept could be applied to the use case that handles traffic control on arterials to provide drivers with a recommended speed with which to progress along a corridor to encounter all green lights. A further extension of this could also be applied to longitudinal control (speed) of an automated vehicle as it progressed along a corridor.

KEY OUTCOMES

Key outcomes of these development activities are:

- Red Light Violation Warning
    - Red light negation warning: drivers are warned in case of a high probability of their own vehicle red light violation.
    - Red light violator warning: drivers are warned of the red light violation of another vehicle.
    - Emergency vehicle warning: drivers are warned to make way for an approaching emergency vehicle that will run the red light.
- Turning warning
    - Oncoming traffic: drivers are warned while turning, to give way to possible traffic coming from the opposite direction having green in the same phase.
    - Crossing vulnerable road users: drivers are warned while turning to give way to in parallel crossing pedestrians and/or bicycles having green in the same phase.
    - Messages from the Red-Light Violation Warning service could come from an RSU communicating via 802.11p or a traffic management center communicating via 3G/4G. Depending on the use case, system design and processing capabilities of the equipment, threat assessment and the generation of warnings could be done by the infrastructure system or the in-vehicle system
- Road Hazard Warning
    - Reduce incidents by sending warning messages to drivers to raise their attention level and inform them about appropriate behavior. Static road hazards have fixed spatial and temporal properties (e.g. road works), while dynamic road hazards can occur anywhere and/or at any time (e.g. queues and traffic jams). Identification of static road hazards is done manually and requires an organizational process that also secures the temporal validity. Detection of dynamic hazards relies on a sensor-based approach with timeliness as the primary concern. Road Hazard Warnings are messages that could come from: a (temporary) RSU communicating via 802.11p, a

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Services_for_Deployment/links/567712f608ae125516ec05fb/Compass4D-Cooperative-Mobility-Pilot-on-Safety-and-Sustainability-Services-for-Deployment.pdf?origin=publication_detail traffic management center communicating via 3G/4G or a stationary vehicle communicating via 802.11p.

- Energy Efficient Intersection
    - GLOSA: drivers receive traffic light state information and advice for the most energy efficient speed and deceleration strategy to approach the intersection. On arterials with multiple intersections this implies platoon progression.
- Green priority
    - Heavy goods vehicles (HGV's), public transport vehicles and emergency vehicles receive green priority at traffic lights.
    - Idling stop support: time-to-green information is used by the in-vehicle application for engine control and engine turn off.
    - Start delay prevention support: time-to-green information is used by the in-vehicle application to minimize time loss at the start of green due to engine start, reaction time, etc.

Different levels of green priority can be distinguished. The lowest level of priority results in extension of the current phase while the highest level of priority results in termination of the current phase to switch to the required phase. Priority level depends on the vehicle type. Messages from the Energy Efficient Intersection Service could come from an RSU communicating via 802.11p or a traffic management center communicating via 3G/4G.

2.5.7 C-ITS CORRIDOR: ROTTERDAM – FRANKFURT/M. – VIENNA[39]

RESEARCH OVERVIEW

German, Dutch, and Austrian road operators started the gradual introduction of cooperative systems in Europe. This cross-national European ITS Corridor is envisioned to introduce deployment-level Cooperative Intelligent Transport Systems (C-ITS) technologies in the real world. The project is designed to phase-in various applications over time. The initial applications will be construction warning and probe vehicle data for traffic management. These were chosen for the potential to deliver end-user benefits even in a day-one environment of limited roadside devices and equipped vehicles.

RELEVANCE TO CTCS RESEARCH

The Road Work Warning application could be applied to the lane management use case as part of CTCS. If the location of an active construction zone can be communicated to a traffic management center, this information could be relayed to drivers upstream of the work zone, so they can better anticipate the work zone and potentially improve mobility through the work zone.

The Vehicle Data for Traffic Management application could play an important role in the ICM use case. The implementation of ICM strategies relies on accurate traffic management data. CV data that is broadcast by vehicles can be captured by RSE, aggregated, and used to generate performance measures. The use of CV data to generate these measures has the potential to be more robust compared to existing traditional ITS detection equipment. However, it is important to note that the ability of CV data to generate robust measures is highly dependent on the penetration of vehicles that are equipped with CV technology.

[39] http://www.c-its-korridor.de/?menuId=1&sp=en

KEY OUTCOMES

Key outcomes of these development activities are:

- Road Work Warning – RWW - Approaching vehicles get information about road works and the traffic situation directly before construction sites in addition to information on static traffic signs. Furthermore, the exact position of road works will be sent to the traffic control center. At present, there is no such information available in a balanced geographic basis. In the period from June 8, 2017 to July 27, 2017, around 100 test trips to 53 different use cases took place in the Frankfurt area with the participation of automotive manufacturers and suppliers as well as interested participants in the test area. The newly developed technology was tested under real road conditions.
- Vehicle Data for Traffic Management (CAM, DENM Aggregation) - Currently traffic data can only be detected by using especially installed traffic data acquisition infrastructure. Event driven information (e.g. emergency breaking warning) can't be detected at all. By using roadside C-ITS infrastructure, in-vehicle data as well as traffic events (safety-relevant data and traffic data) can be detected and distributed to traffic control centers in the future. The roadside C-ITS infrastructure will continue to collect data from vehicles and transfer it to the Traffic Control Centre. It is solely about safety related information as to incidents on the road, their capacity as well as interference in traffic flow. So far, traffic management can only partly rely on vehicle-based data because it is often not available at all or only to a certain extent, and there is limited infrastructure from which to collect this data. Once this data becomes more available, it can be used to avoid congestion through optimized route and network control, incident management, access to vehicle data independent from commercial suppliers, and to be used in other applications that also use C-ITS technology.

2.6 RAILROAD CROSSING VIOLATION WARNING

This use case explores how DSRC technology might be used to improve safety at grade-level rail crossings, particularly in cases of unsignalized crossings in rural locations, or in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic.

2.6.1 VEHICLE-TO-INFRASTRUCTURE RAIL CROSSING VIOLATION WARNING CONCEPT OF OPERATIONS[40]

RESEARCH OVERVIEW

This recent Battelle Memorial Institute study created a Concept of Operations document to describe the V2I Rail Crossing Violation Warning (RCVW) safety application to manage how roadway vehicles are warned when approaching highway-rail intersections (HRI) and when there is a violation of the HRI active warning/protective system. By integrating this warning system with the introduction of CV roadside architecture, they hope to increase safety, improve traffic, and subsequently create environmental benefits through reduced energy consumption.

RELEVANCE TO CTCS RESEARCH

Based on an analysis of the USDOT accident database, there is a need for a more effective solution to reduce incidents at HRIs. So, this report looks to create a CV system that uses ITS technology to provide in-vehicle

[40] https://rosap.ntl.bts.gov/view/dot/31813

warnings of HRI violation based on active warning/ protective devices. This system involves a track-circuit based train detection system, RSU, necessary equipment to communicate with the On-Board Unit (OBU), and future train detection technology. MMITSS logic, in the form of CTCS could support this added feature.

KEY OUTCOMES

Key outcomes of this research are:

- Because different railroad agencies operate and own their own wireless data network, an agreement will be needed to share this data across agencies with uniform standards.
- Implementing this system of safety applications led to a reduced number and severity of HRI related incidents and improvements in traffic flow.
- There is a risk in the future that motorists will become dependent on these warnings, in which case a failsafe will need to be created to let motorists know when to not depend on them in case of malfunctions.

2.6.2 HIGHWAY-RAIL INTERSECTION CRASH TAXONOMY FOR CONNECTED VEHICLE SAFETY RESEARCH[41]

RESEARCH OVERVIEW

This report investigates the use of V2I and V2V applications to improve the safety of those involved with HRI to quantify the human and economic impact of HRI accidents that could have been prevented through CV technology and to identify what these technologies would most appropriately be. Through analyzing databases, such as those available from USDOT and Federal Railroad Administration (FRA), they found that they could apply V2V, V2I, or a combination of those systems to most pre-crash scenarios.

RELEVANCE TO CTCS RESEARCH

Although historic data shows that there has been a gradual decrease in incidents since the implementation of flashing lights and gates, there is still a need to use emerging technologies such as CV, V2V, and V2I technologies to address HRIs. For example, 13% of incidents occurred at HRIs due to vehicles driving around a closed gate when a train was approaching, which shows that current warning systems are not always enough to prevent incidents.

KEY OUTCOMES

Key outcomes of this research are:

- Commercial vehicles compose only 20-25% of all HRI incidents but are responsible for 45-55% of annual motor vehicle damage costs
- Between 2008 to 2012, 80% of all incidents and 88% of all fatalities involved a train hitting a vehicle.
- It is difficult to pinpoint specific infrastructure needs to address HRI incidents since a small number of incidents every year cause most the damage.

[41] https://rosap.ntl.bts.gov/view/dot/12200

3 HIGH-LEVEL TECHNOLOGY READINESS LEVEL ASSESSMENT

As mentioned previously, TRL assessments are a methodology for estimating the current maturity level of a technology. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology. As applied to this effort, this process helps to establish a clear understanding of current R&D efforts and is a factor in determining a path for future research. Table 1 provides descriptions of the TRL levels.

Table 1: Technology Readiness Levels[42]

TRL	Definition	Description
1	Basic principles and research	• Do basic scientific principles support the concept? • Has the technology development methodology or approach been developed?
2	Application formulated	• Are potential system applications identified? • Are system components and the user interface at least partly described? • Do preliminary analyses or experiments confirm that the application might meet the user need?
3	Proof of concept	• Are system performance metrics established? • Is system feasibility fully established? • Do experiments or modeling and simulation validate performance predictions of system capability? • Does the technology address a need or introduce an innovation in the field of transportation?
4	Components validated in laboratory environment	• Are end-user requirements documented? • Does a plausible draft integration plan exist, and is component compatibility demonstrated? • Were individual components successfully tested in a laboratory environment (a fully controlled test environment where a limited number of critical functions are tested)?
5	Integrated components demonstrated in a laboratory environment	• Are external and internal system interfaces documented? • Are target and minimum operational requirements developed? • Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?

[42] https://www.ncbi.nlm.nih.gov/books/NBK201356/

6	Prototype demonstrated in relevant environment	• Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? • Was the prototype tested in a realistic and relevant environment outside the laboratory? • Does the prototype satisfy all operational requirements when confronted with realistic problems?
7	Prototype demonstrated in operational environment	• Are available components representative of production components? • Is the fully integrated prototype demonstrated in an operational environment (i.e., real-world conditions, including the user community)? • Are all interfaces tested individually under stressed and anomalous conditions?
8	Technology proven in operational environment	• Are all system components form-, fit-, and function-compatible with each other and with the operational environment? • Is the technology proven in an operational environment (i.e., meet target performance measures)? • Was a rigorous test and evaluation process completed successfully? • Does the technology meet its stated purpose and functionality as designed?
9	Technology refined and adopted	• Is the technology deployed in its intended operational environment? • Is information about the technology disseminated to the user community? • Is the technology adopted by the user community?

The TRL Scale is grouped into four categories, basic research, applied research, development, and implementation, as shown in Table 2. Given that the outcome of the analytical process outlined in this report is to ultimately define a research plan, it focuses on the basic research, applied research, and development categories.

Table 2: Four Categories of TRL Scale[43]

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

[43] Source: Federal Highway Administration

		8. Technology proven in operational environment.	

3.1 ARTERIAL/SURFACE STREETS WITH TRAFFIC CONTROL AND RAMP METERS

Table 3 provides a high-level TRL assessment of the Arterial/Surface Streets with Traffic Control and Ramp Meters use case.

Table 3: Arterial/Surface Streets with Traffic Control and Ramp Meters High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	Although many vehicles track data on speed, acceleration, location, etc., few vehicles are equipped to communicate this information with each other or the infrastructure despite the technology existing. Using sensor data from vehicles and V2I communications, researchers have shown that they can make more informed decisions on how to optimize traffic based on algorithms and V2I/V2V communications.
2	Application formulated	Traffic control and ramp metering were identified to be particularly useful in high traffic turbulence areas, such as intersections and bottlenecks. These applications can contain a combination of technologies and approaches, such as CoopRM, CACC, VSL, and queue warning, and can fall under larger traffic improvement and safety strategies, such as MMITSS. Vehicles that are properly equipped to communicate with RSUs can communicate this information to drivers through in-unit displays.
3	Proof of concept	As part of the simulation tests, traffic control systems and ramp meters were tested using variable penetration rates to see the resulting traffic performance. This includes quantifiable benefits seen in vehicle miles traveled, vehicle hours traveled, speeds, and improved maneuvering capabilities.
4	Components validated in laboratory environment	Application such as MMITSS has been tested and validated in tested beds in California and Arizona. Due to the inherently different nature of the test beds, it allowed researchers to test MMITSS across multiple controlled factors. In one study done by University of Arizona and PATH, two test scenarios were used to see the impact it would have for corridors with a lot of trucks that need priority and, in another area, where it was more pedestrian and transit friendly with typical commuter traffic. The concept however has been mostly focused on a single intersection and does not include ramp meters or coordinated/adaptive corridors.

3.2 MULTI-MODAL ASPECTS INCLUDING TRANSIT, FREIGHT, PEDESTRIANS, BIKES, ETC.

Table 4 provides a high-level TRL assessment of the Multi-Modal Aspects including Transit, Freight, Pedestrians, Bikes use case.

Table 4: Multi-Modal Aspects including Transit, Freight, Pedestrians, Bikes, etc. High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	As part of integrating multi-modal aspects into a traffic scenario, researchers have examined various technologies which utilize detectors, RSUs, communication devices, OBUs, etc. to create a network that efficiently and safely routes traffic so that all users can proceed through. For example, these include Pedestrian Warning Systems, Circle Eye, and Driver Assist Systems, which all work through integrating pedestrians, bicyclists, motorcyclists, and buses into the vehicle and driver decision making process.
2	Application formulated	Specific system applications have been identified in integrating multi-modal aspects through CAV technologies. This involves pedestrian data, such as location, being fed into the system through either the detectors on buses and vehicles or manually through apps that the user has on their mobile devices. While some applications have been only developed conceptually, many of the applications have been initially tested at a pilot site. Other applications include: + Warnings about violations by vehicles, bikes, pedestrians. + I2X (infrastructure to everything) technology, through which CAVs learn about pedestrian and bike intentions. Cyclists use I2X for give-me-green requests. + Providing info about presence of vehicles, bikes, and pedestrians in particular lanes and crosswalks: informs CAVs about activity in their blind spots.
3	Proof of concept	Due to the variable nature of how the receiving driver would interpret the message sent from the detector system, the success of these applications was judged based on more qualitative metrics from surveys, such as how effective/easy was the technology to use, success rate of detecting pedestrians, reaction time, etc. Furthermore, the surveys provided more feedback on what features of the technology require add-ons or redevelopment, like in low light or night scenarios, and will need to address these before being considered finished.
4	Components validated in laboratory environment	As part of the implementation analysis, the necessary equipment and technology requirements have been identified, although there are mixed results on the feasibility of implementing the strategies. For example, based on the studies done by RTA and other agencies, one of the biggest inhibitors of fully implementing pedestrian warning systems was the cost of $1,500- $2,500 per vehicle. Likewise, for mobile apps to be an effective portion of any technology implementation, it would need to start with a high penetration rate for the benefits to be visible.

		Further, the limited ability of mobile phones to provide accurate location also precludes widespread adoption.

3.3 CONNECTIVITY AND EARLY AUTOMATION SUCH AS LEVEL 1 LONGITUDINAL CONTROL

Table 5 provides a high-level TRL assessment of the Connectivity and Early Automation Such as Level 1 Longitudinal Control use case.

Table 5: Connectivity and Early Automation Such as Level 1 Longitudinal Control High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	Level 1 automation related technologies, such as longitudinal and lateral controllers, have been identified as key components to controlling a vehicle's acceleration and steering respectively. Additionally, when coupled with V2V or V2I communications, level 1 automation can improve a vehicle's operational efficiency. Thus, continuous research has been conducted on optimizing the algorithms used by the vehicle to lower emissions and fuel consumption and improve efficiency.
2	Application formulated	Early level 1 automation technologies and use cases have been identified to assist vehicles in detecting each other and adjusting speed accordingly. For example, it is possible to leverage V2V communications to enable vehicle platooning and V2I communications to send signal phase and timing (SPaT) and other information from ITS devices to vehicles to control the speed of vehicles.
3	Proof of concept	Although level 1 automation technologies are deployed and available commercially for the public to use, most of the applications are for freeways, such as ACC. More advanced versions, particularly for signalized arterials, using V2V or V2I communications and related algorithms continue to be tested. One of the biggest limitations with these algorithms is the lack of connected vehicles present for testing. As such, they are not system feasible yet, although they do show consistently improved vehicle performance when tested in simulations.
4	Components validated in laboratory environment	For the longitudinal control algorithms to be validated, research projects typically use a test site with relatively controlled conditions and sensors in the test vehicle to monitor the performance. Based on the limited studies done to date, they can prove that connected level 1 automation does in fact improve the vehicle performance.

3.4 CONNECTED VEHICLE INTEGRATED CORRIDOR MANAGEMENT (ICM)

Table 6 provides a high-level assessment of CV ICM use case.

Table 6: CV ICM High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	The basic scientific principles support the idea that ITS technologies can efficiently and proactively manage the movement of people and goods in a corridor. ICM integrates CV and ITS technologies with multimodal and multijurisdictional strategies to optimize existing infrastructure. Based on the experience from the ICM deployments, a methodology has been developed to help other agencies forecast and assess the benefits and implications for their corridor.
2	Application formulated	The advancement of ITS/CAV technologies in conjunction with ICM has proven that it can help agencies deal with the growing availability of data being captured and the emerging normality of having multiple agencies involved with managing a single corridor. Examples: + At freeway ramps and arterial junctions, CAV data can help estimate queues and enable ramp metering and signal coordination to prevent spillbacks into arterials from on-ramps, and to freeways from off-ramps. + Speed advisory on major arterials. CAVs can optimize the speed to catch the green wave. For intersections, it improves progression quality and minimizes idle green. + CAVs can be used to control vehicle flow at arbitrary locations, basically implement VSL (VSL was mentioned in 3.1).
3	Proof of concept	During the deployment, USDOT looked at the traffic volumes; speeds; awareness, use, and compliance with pre- and en-route traveler information; and costs. Moreover, based on these results, they show that ICM does lead to improved travel information and awareness for drivers, more efficient use of the corridor lanes, and improved emissions.
4	Components validated in laboratory environment	As part of USDOT's ICM Initiative, ICM was deployed at two demonstration sites to analyze the system performance "as deployed" at the test site with a framework of key activities required after analysis presented in the research. The ICM Initiative builds upon past IMTMS in the network to integrate real-time data and predictive analysis.
5	Integrated components demonstrated in a laboratory environment	Compared to baseline performance metrics, USDOT programs such as AERIS have shown that ICM can lead to improved travel time savings, environment benefits, and other travel performance metrics. These initiatives build on past ICM implementations to incorporate CAV data and communication between vehicles and infrastructure.

6	Prototype demonstrated in relevant environment	The ICM Deployment is composed of a lot of the vital components that will move onto to be integrated for public deployment. The test sites in San Diego and Texas allow USDOT to test the technology and strategy across different environments that would simulate common problems when openly deployed for the public. Moreover, the analysis includes incident matching, which investigates the response the ICM system created to deal with incidents.

3.5 LANE MANAGEMENT

Table 7 provides a high-level TRL assessment of the Lane Management use case.

Table 7: Lane Management High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	Lane management has shown that through using proper strategies that are well informed through CAV data, such as dynamic lane reversal routing and scheduling, these strategies have led to improved capacity and overall efficiency. These strategies involve using V2I and V2V communication and algorithms to analyze real-time data and advise best practices for moving human-operated and CAV vehicles across a given corridor.
2	Application formulated	Lane management has been identified as a way of addressing higher penetration rates of CAVs coming to market and integrating them with existing human drivers. Moreover, for already existing CAVs, it's shown that it can be implemented for more complicated applications like lane reversal to combat peak period congestion without building significantly more infrastructure. Generally, this involves RSUs, OBUs, CAVs, and CAV technologies. Further, it would require roadside signage to make drivers of non-equipped vehicles aware of the lane management rules.
3	Proof of concept	Lane management is analyzed based on congestion levels, travel times, speed, and other performance metrics specific to the application. Using simulations with varying criteria established, researchers have proven that the algorithms and technologies can lead to successful lane changes and lane reversals to help manage traffic using existing infrastructure.
4	Components validated in laboratory environment	The algorithms and concepts behind lane management have been tested as part of simulations using set variable values for capacity, demand, etc. to emulate different traffic scenarios. Furthermore, they could plan for developing technologies in the future by testing for degrees of more aggressive CAV technologies and the impact it would have on lane change mechanisms.

3.6 RAILROAD CROSSING VIOLATION WARNING

Table 8 provides a high-level TRL assessment of the Railroad Crossing Violation Warning use case.

Table 8: Railroad Crossing Violation Warning High-Level Technology Readiness Level Assessment

TRL	Definition	Comments
1	Basic principles and research	CAV technologies are vital to helping the selection of the appropriate signal preemption plan prior to a train's arrival and the signal transition plan after the preemption based on CV data, and warning drivers about imminent danger at railroad crossings. They allow multi-modal communication between the train and vehicle via RSU so that the driver is given real time warning.
2	Application formulated	Historically, applications like flashing lights and gates have led to a decrease in incidents. When coupled with V2I communications, the nearby traffic signals can provide better signal preemption control and after-preemption transition control which improve the safety and efficiency at railroad crossings. In addition, with V2I communications and warning applications, a lot of incidents that occur due to the driver ignoring the warning signs and driving around barriers could be addressed. Allowing the vehicle and other parties involved like the train know when drivers are negligent can help them react as well to prevent crashes.
3	Proof of concept	When implementing a successful CAV-based railroad crossing warning system, success depends on whether it leads to improved traffic, decreased number of incidents and severity of incidents, and cost benefits. In the case that drivers are negligent, it also provides the opportunity to implement a failsafe within the warning system.
4	Components validated in laboratory environment	One system used to warn vehicles requires a track-circuit based train detection system, interconnected crossing warning devices (lights and gates) and the nearby traffic signal control system, RSU, necessary equipment to communicate with the OBU, and future train detection technology. In addition, by using databases from USDOT and FRA, researchers can identify applicable incident scenarios and sites where CAV applications would have been effective.

4 CONCLUSIONS AND NEXT STEPS

This report researched and documented a set of additional traffic control related CAV use cases that extend beyond the individual signalized intersections that were previously researched as part of the separate MMITSS research projects. This report includes a discussion on other functions and applications that build from the original MMITSS concepts and which promote enhanced mobility between intersections and adjacent freeway/ramp/arterial networks. This assessment reviewed domestic and international research activities and also considered the involvement of technology vendors, including communications firms. The findings proposed in this report are structured around six previously agreed-to "use cases". Use cases are defined as a list of actions that document the interactions between a user and a system to achieve a specific goal. The selected use cases include:

- Arterial/surface streets with traffic control and ramp meters
- Multi-modal aspects including transit, freight, pedestrians, bikes, etc.
- Connectivity and early automation such as Level 1 longitudinal control
- CV integrated corridor management
- Lane management
- Railroad crossing violation warning

The primary outcome of this work product was to identify the gaps associated with the identified use cases, and to prepare to solicit stakeholder input, as part of Task 4, to better articulate the research areas and priorities, user needs, transformative benefits or goals, and corresponding performance measures associated with these use cases. As part of this task, a preliminary TRL assessment was made based primarily on the review of existing literature and the research team's experience. This initial assessment is captured in Table 9.

Table 9: Summary of High-Level TRL Assessments

Application	Overall TRL Assessment	Category
Arterial/Surface Streets with Traffic Control and Ramp Meters	4 - Components validated in a laboratory environment.	Applied Research
Multi-Modal aspects including Transit, Freight, Pedestrians, Bikes, etc.,	4 - Components validated in a laboratory environment.	Applied Research
Connectivity and Early Automation such as Level 1 Longitudinal Control	4 - Components validated in a laboratory environment.	Applied Research
CV ICM	6 - Prototype demonstrated in relevant environment.	Development
Lane Management	4 - Components validated in a laboratory environment.	Applied Research
Railroad Crossing Violation Warning	4 - Components validated in a laboratory environment.	Applied Research

4.1 SUMMARY OF FINDINGS FOR USE CASES

The identification of gaps in applied research presents a challenge unless it has been determined what the definition of success looks like. The TRL is one factor, but even a Level 8 or 9 solution that doesn't fulfil a real need remains a gap. The project team has attempted to identify definitions of success such that an analysis of the existing research, the TRL level and the end goal can together be used to identify the gaps. Following are a first attempt at satisfying this goal, first by restating the use case, followed by an expectation of output, and then the gaps. In addition, while the research roadmap is intended to include all research actions the team is interested in pursuing, there is a need to prioritize those that will be pursued first. These have been identified as prioritized next steps under each use case, with results of a prioritization exercise between these next steps across all six use cases included at the end of the section.

4.1.1 ARTERIAL/SURFACE STREETS WITH TRAFFIC CONTROL AND RAMP METERS

Definition: This use case explores how connectivity will allow vehicles to interact with ITS technology beyond the individual traffic signal controllers; such as ramp meters, adaptive signal systems, etc.; in order 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.

Definition of Success: At a high level, success is defined as the ability for vehicles and drivers to make more informed decisions when traveling on arterial/surface streets, and for the system to be more efficiently coordinated between subsequent intersections and other traffic control devices such as ramp meters.

For ramp metering, the system would provide information to the vehicle and driver about the extent of queues and the time in queue for each metered ramp. When queues are excessive, the system would provide information on ramps that would meet the travel needs that would provide less overall travel time or less time in queue. In addition, connected vehicles would provide information on time in queue and extent of queue to the system. Finally, vehicles would provide important information to the ramp metering algorithm that would allow for improved information and may even lead to the development of improved metering algorithms.

For adaptive signal systems, like how present-day systems are comprised of upstream and often downstream detectors, adjusting timing beyond just the next signal, the CV environment would use the trajectory information available to it to improve these algorithms.

Gaps: There is no standard message for queue length or time in queue messages to be output from the controller or central ATMS for a ramp meter. SPaT messages can have back of queue information but it is not always populated. There also are typically no accurate means of determining queue lengths or time in queue in real time, beyond the estimations based on a very limited number of queue detectors on ramps or potentially from basic safety messages from the few vehicles that are connected.

In terms of adaptive signal control, it is common knowledge that commercial signal control vendors are exploring trajectory-based detection, presently with video or radar detection, but with an eventual goal of CV-enabled. The challenge in this case is the interim period where both equipped and non-equipped vehicles co-exist, requiring a way to not double-count a vehicle.

Prioritized Next Steps:

- Queue length detection: Pursue reliable queue length detection and/or information on the location of the back of a queue.
- Virtual detection: Instead of just using infrastructure to detect vehicles and/or back of queue locations, a system could use connected vehicles as probes. This would involve vehicles that are equipped being able to sense the unequipped vehicles around them and sharing data with a system about vehicles in front of, behind, and possibly next to the equipped vehicle.

4.1.2 MULTI-MODAL ASPECTS INCLUDING TRANSIT, FREIGHT, PEDESTRIANS, BIKES, ETC.

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

Definition of Success: Success is defined as enhanced safety and mobility for all modes.
For transit and freight, this includes reducing delay and emissions by adjusting operations to minimize the amount of start-up lost time that is experienced in a heavy vehicle during an uphill approach or unnecessary hard braking on a downhill approach to either a traffic signal or ramp meter. It also includes exploring additional options for first/last mile travel of both passengers and goods. For pedestrian and bikes, this includes reducing delay experienced by a modal user waiting at a traffic signal for the right of way to cross and improving safety by focusing on enhanced detection of vulnerable road users (also including scooters and skateboarders).

Gaps: For transit and freight, there will need to be an automated vehicle location device (trajectory) and a route planning tool (destination) integrated with the vehicle for a signal to know how to balance signal operations for an approaching heavy vehicle. It may also be useful to have information on current vehicle occupancy, especially considering that transit vehicles come in varying sizes and capacities that may have similar current occupancy (or other ways to prioritize between different transit vehicles).

- A signal system would need to be able to modify signal phases via green extension or early red termination while maintaining the coordination plan developed for the corridor.
- A ramp metering system would need to be able to increase metering rates based on the approach and modify upstream, and some downstream, metering rates so that the operations of the freeway are balanced and maintained. (Metering rates at downstream ramps that are still upstream of the bottleneck can be adjusted to account for increased rates at ramps with heavy vehicle priority.)

For pedestrian and bikes, there will need to be level of automated location detection (trajectory) and route planning tool (destination) via personal device application for a signal to know when to grant the right of way to reduce delay. This application will need to provide trajectory and destination information to the signal system for optimization between vehicular and pedestrian operations. Experience to date has shown that the detection of pedestrians and the detection of cyclists requires very different systems and algorithms and is best pursued separately.

Prioritized Next Steps:

- Ped safety: Exploring opportunities to enhance pedestrian safety, including during degraded conditions such as low-light, poor weather, and pedestrian non-compliance.
- Bike safety: Separately determining how to improve cyclist safety, considering the operational profile of cyclists (i.e., transitioning between operating in mixed or separated traffic).

4.1.3 CONNECTIVITY AND EARLY AUTOMATION SUCH AS LEVEL 1 LONGITUDINAL CONTROL

Definition: This use case explores how connectivity and partially-automated vehicle functions will allow operational improvements and possible roadway capacity expansion through connectivity and longitudinal controls. For example, it is possible to achieve shorter headways between vehicles travelling in platoons and this can allow more vehicles per lane per hour. This use case leverages vehicle-to-vehicle (V2V) communications to enable vehicle platooning but also vehicle-to-infrastructure (V2I) communications to communicate the arrival of vehicle platoons to intelligent transportation system (ITS) field equipment – mainly traffic signal controllers. This use case also leverages V2I communications to send signal phase and timing (SPaT) and other information from ITS devices to vehicles to control the speed of vehicles.

Definition of Success: The vision of success will vary depending on the currently capabilities and fleet penetration of CAVs, but overall involves blending the two technologies together to enhance their collective benefits.

More specifically, near-term success would focus on the benefits provided to an individual CAV such as providing SPaT data to a CAV to enable a smoother, environment-friendly drive through an equipped intersection or series of intersections. Mid-term success would involve the bunching of CAVs into platoons and the ability of a signalized corridor to be able to respond accordingly (e.g. adapt signal timing to accommodate an entire CAV platoon). Long-term success assumes a heavy saturation of CAVs travelling along a corridor at close enough distances to enable higher vehicle capacity on arterials.

Gaps: Connectivity and early level 1 automation has been successfully modelled in traffic simulations and successfully prototyped and demonstrated in controlled settings such as isolated test intersections on research campuses. A key gap is the limited number of connected intersections and the lack of CAVs to test on a larger scale at these intersections. This makes it very difficult to test the feasibility of adapting signal timing to accommodate CAV platoons. Additionally, most tests so far have been conducted with very simple traffic signals (i.e. fixed time) so future tests with CAVs need to be conducted at intersections with more advanced signal timing schemes. Finally, in order for this use case to be successful, the CAVs need a combination of reliable V2V, V2I and internal sensors that are all linked to level 1 automation in the vehicle. There are not many vehicles today that have this degree of functionality.

Prioritized Next Steps:

- MAP: Information on roadway and intersection design is not standardized across agencies and across vehicle platforms, which makes it inefficient to create MAP files and could lead to issues if different tools require different levels of accuracy. There is a need to add more detail and consistency to these messages.
- Position correction: Vehicle manufacturers need lane-level accuracy to improve their positioning, but this is not always available.
- Real time signal optimization for groups: Whether vehicles are traveling in platoons or in strings, they need the ability to communicate with infrastructure in real-time to help optimize signal timing.

4.1.4 CONNECTED VEHICLE INTEGRATED CORRIDOR MANAGEMENT

Definition: 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).

Definition of Success: For CV-ICM, success is defined as the ability of the system to provide information to users about conditions compared to the typical in advance of the decision point so that they can determine what is their best option based on their trip end.

Gaps: Database integration of historical, and real-time conditions to be segmented and displayed for individual use

- Known destinations via route planning tool, for each vehicle would better allow the system to customize the route options displayed in a connected vehicle. Normal ITS application picks major landmarks as the destination, useful for a 100+ mile trip but not as useful for commutes with destinations on either side of a freeway bottleneck.
- ATMS may have a limited ability to process both historical average and current travel time information, based on speeds across a segment.

Prioritized Next Steps:

- Interagency coordination: Without strong coordination between different agencies within a jurisdiction, strategies like ICM will not be possible.

- Data sharing: There need to be better policies and procedures for sharing data between agencies and with private companies. ICM is not just traffic management, but also the ability for users to make informed decisions based on the data available to them. Data needs to be both clean and accessible, while mitigating any potential privacy concerns.

4.1.5 LANE MANAGEMENT

Definition: 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, allow use of shoulders as temporary travel lanes, and/or prohibit or restrict types of vehicles from using lanes.

Definition of Success: For lane management, success would be measured by maximizing the utilization (highest capacity and safety) of the existing built infrastructure based on current traffic conditions. The ability to open a shoulder for use during a peak period to increase capacity, providing advisory speeds when weather conditions make the design speed unsafe to improve safety, lane use control to move vehicles over in advance of an incident or in a work zone (mobile or long term) to reduce secondary collisions.

Gaps: Lane management will need accurate vehicle detection equipment for the mixed vehicle fleet (connected vs non-connected) to determine when these applications should be applied and where to maximize the facility's use.

- Hard shoulder running, or use of the shoulder as a travel lane during peak periods, would benefit from knowing when to allow and restrict access to the lane. The use of the shoulder for travel can be beneficial for capacity, but also increases the safety risk that results from congestion caused by stalled or broken-down vehicles on the traveled lanes. In addition, there may be disabled vehicles that need a safe refuge area on the shoulder, which would lead to either closure of the shoulder travel lane or not opening the shoulder to begin with. Therefore, traffic conditions should determine the use of the lane rather than a static set of hours to optimize the use of the shoulder and minimize the time without a safety refuge area when the added capacity is not needed.
- Advisory speeds based on weather conditions to prevent incidents or secondary crashes will incorporate RSE for monitoring and OBUs to share information in connected vehicles and traditional ITS devices for non-connected vehicles
    - In known problem areas, sharp curves or crest/sag conditions or long-term construction jobs, a fully instrumented roadway might be justified from a cost standpoint to meet the initial need.
    - However, non-recurring congestion events (incidents, mobile, or emergency maintenance) which would also benefit from advisory speeds. Having a connected fleet would make it easier to share information, especially outside of urban roadways where these types of events happen more frequently.

Prioritized Next Steps:

- MAP (lane level/dynamic mapping): Precision in lane geometry that can be modified in real time to allow for dynamic shifts in lane availability and other restrictions (such as a bus-only lane during peak periods or a reversible travel lane).
- Lane availability: Information, especially in rural areas, on lane closures (due to incidents, road work, etc.) at a time when it allows the user to make a more informed decision in response to this change in the roadway network.

4.1.6 RAILROAD CROSSING VIOLATION WARNING

Definition: This use case explores how DSRC technology might be used to improve safety at grade-level rail crossings, particularly in cases of unsignalized crossings in rural locations, or in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic.

Definition of Success: Information on delay times or times in queue for rail crossings in general and especially for urban areas close to switching yards or other locations where rail operations block grade crossings for long stretches of time. Drivers could choose grade separated crossing at longer distances or could divert their trip temporarily if the time in queue is extreme.

At signalized railroad crossings, success would be measured by improved intersection performance measures such as average queue length and delay, timely warning to avoid a potential crash, and reduced number of collisions at crossings.

At unsignalized crossings, success would be measured by timely warning and reduced number of collisions at crossings.

Gaps: Information on rail operations is the biggest gap. Information is needed on the location, speed, and length of trains.

At signalized crossings, the traffic signal controller needs to have the capability of implementing multiple preemption plans and transition plans and selecting the appropriate plans based on real-time performance measures utilizing V2I communications. At unsignalized crossings, train AVL data would be required for determining the presence and estimating its arrival time at crossings. For both signalized and unsignalized crossings, penetration rate of equipped vehicles is one of the key gaps for deploying this application. Cellular-based V2I communication could be a viable approach for warning drivers about the approaching train.

Prioritized Next Steps:

- Advanced information for travelers: Data that is provided to vehicles and drivers at the right time so they can, for example, travel a longer route that does not cross a blocked at-grade crossing, or at least know how long a crossing will be blocked to reduce frustration.
- Advanced information for traffic engineers: Data that can inform longer term planning decisions, such as which crossings to upgrade/separate. A lot of private railway companies claim their data is private and are not willing to share it for security reasons, so this may be more a policy issue than a technology issue.
- Imminent safety: Warnings to vehicles and drivers on approaching rail vehicles and potential conflicts. Will likely need to be a redundant system with multiple options for information collection and sharing.

4.2 PRELIMINARY RESULTS FROM THE STAKEHOLDER NEEDS WORKSHOP

The outcomes of this report were used as the starting point for Task 4, which consists of a detailed assessment of the readiness of the various use cases and will serve as the basis for the research plan.

During the April 30, 2019 stakeholder meeting, the identified prioritized next steps were voted on using the survey tool Mentimeter. 30 people voted in the first Mentimeter exercise. Participants listed three actions and voiced that they generally did not prioritize between the three actions they provided, so all three are weighted equally in the following graph. 13 of the 90 suggestions were just the application scenario and not an action – these are included at the bottom of the graph.

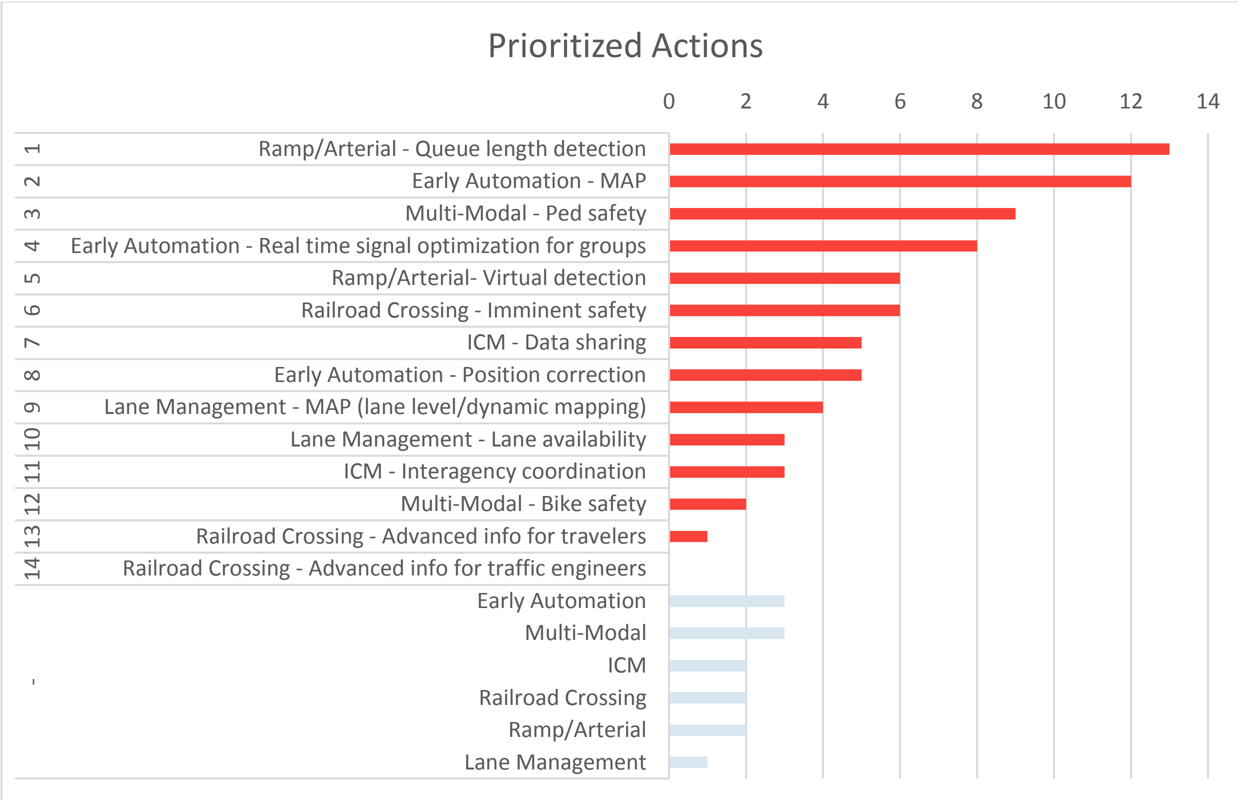

Figure 4-1: Stakeholder Meeting Results on Prioritized Actions

The second Mentimeter exercise was to prioritize the six use cases, which led to the following results:

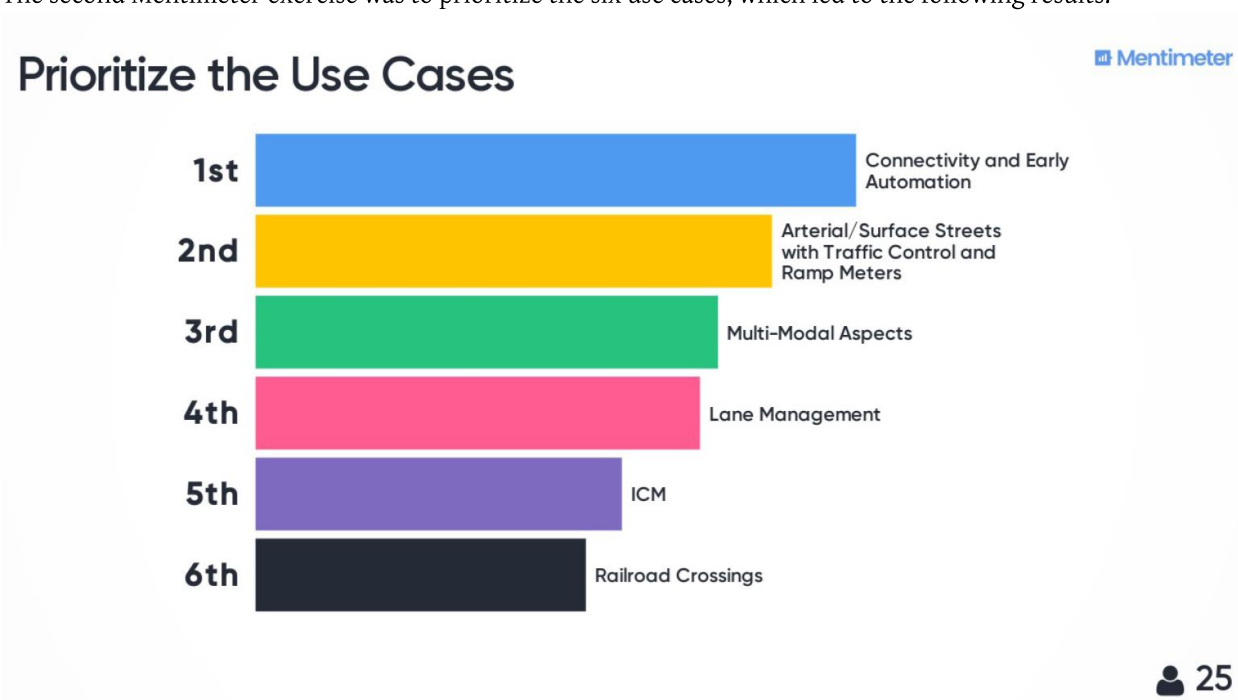

Figure 4-2: Stakeholder Meeting Results on Prioritized Use Cases

The group discussed that the railroad crossings application was probably ranked low because the benefit of CV to help meet this need is less clear. In addition, railroad crossing may not be in the traffic engineer's control due to the presence of private operators. Lane management and ICM are also ranked low, which was expected based on the gaps and other concerns voiced throughout the meeting.

Participants added that they tended to rank use cases based on whether they had voted for actions under that use case in the previous list. Participants also tended to pick use cases and actions they could work on right away, such as those that leverage existing deployments. They preferred projects that could likely be implemented quickly, and where results would quickly be achieved. These preferences should be considered when creating the research plan and when determining the earliest steps to pursue within that overall, longer-term research framework.

Detailed results from the stakeholder needs workshop will be documented and used to guide the Task 4: Assessment of Technology Readiness Levels for Priority Research Areas report.

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APPENDIX A

The following summaries were previously included in the main text of the document, but during the review process, were determined to only minimally support the stated use cases. They have been moved to this Appendix to provide some historical traceability for this work.

APPLICATIONS FOR THE ENVIRONMENT: REAL-TIME INFORMATION SYNTHESIS (AERIS)

RESEARCH OVERVIEW

This paper discusses the Eco-Lanes Transformative Concept, which focuses on developing dedicated lanes on freeways, known as eco-lanes, that optimize environmental benefits. These eco-lanes operate like high-occupancy vehicle (HOV) lanes, but one of the key differences is that drivers can utilize environmentally friendly CV applications. Parameters are established for what types of vehicles may enter eco-lanes and how the eco-lanes are set up on the freeway, including number of lanes and the start/end points. The research's main objectives are to determine whether the following are feasible:

- Identify CV applications that can be used for environmental benefits.
- Assist transportation service consumers with making environmentally friendly decisions.
- Identify different forms of data exchange between vehicle to vehicle, infrastructure, and grid.
- Model and analyze CV applications to estimate their potential environmental impact reduction benefits.
- Create a prototype for one of the applications to test its efficacy and usefulness. [44]

RELEVANCE TO CTCS RESEARCH

Some applications discussed in this paper that affects traffic control and ramp metering are eco-lane management, eco-speed harmonization, eco-cooperative adaptive cruise control, and eco-metering. By taking advantage of vehicle-to-vehicle (V2V) and V2I technologies and their capability to record performance data, these applications allow drivers to be more aware of what is happening in their environment and surroundings.

KEY OUTCOMES

Key outcomes of this research are:

- Based on current standards, eco-applications face these limitations:
    - HOV and high-occupancy toll (HOT) lanes are limited geographically by roadside infrastructure.
    - Current applications do not fully utilize real-time traffic and environmental data and are limited to the data from infrastructure-based sensors.
    - VSL and ramp metering systems do not currently collect or use environmental data and thus are optimized for mobility only.
    - Moreover, VSL systems, especially those in the United States, have low levels of speed compliance.
- Vehicles that use Adaptive Cruise Control (ACC) systems instead of CACC require longer minimum gaps between vehicles due to a delay in the sensor.
- There is no in-vehicle monitor to display the parameters established for eco-lanes.
- Also, researchers found the following benefits:
    - ACC has shown to reduce carbon dioxide and NOx by 3% in Rotterdam test research projects and to reduce fuel consumption by 5-10% in California and Southeast Michigan.

[44] https://rosap.ntl.bts.gov/view/dot/3439

- Ramp metering causes 22% decrease in freeway travel times and a decrease in 5.5 million gallons of fuel consumption

CONCEPT DEVELOPMENT AND NEEDS IDENTIFICATION FOR INTELLIGENT NETWORK FLOW OPTIMIZATION (INFLO)- ASSESSMENT OF RELEVANT PRIOR AND ONGOING RESEARCH

RESEARCH OVERVIEW

As part of the USDOT's DMA program, this report investigates the three INFLO applications:

- Queue Warning (Q-WARN) - Provides drivers with a warning when it detects an impending queue backup. INFLO utilizes V2I and V2V communication with vehicles already in queue to alert approaching vehicles their queued status information.
- Speed Harmonization (SPD-HARM) - Adjusts and maximizes the vehicle's speed based on congestion, incident reports, and weather/road conditions. INFLO will use this to communicate with vehicles downstream in congestion their location, type, and the intensity of congestion to calculate the appropriate speeds to minimize incidents.
- Cooperative Adaptive Cruise Control (CACC) - Automatically coordinates speeds amongst vehicles within proximity of each other so that they flow smoothly through a corridor. By using on-board radars, they can maintain consistent gaps between vehicles and improve efficiency.

This analysis and findings provide an understanding of current industry practices and relevant research being conducted so that data is being actively exchanged and managed between detectors involved in these CV applications.[45]

RELEVANCE TO CTCS RESEARCH

Each application utilizes CV technologies to improve on current traffic flow practices. Past case studies have shown that when applied, these applications have led to decreased congestion, improved travel time and mobility, and improved safety. For example, in a pilot project conducted in Missouri with speed harmonization, it was determined that there was a significant reduction in incidents but no mobility gains, which may be due to the low observed compliance rates. Similarly, in New Mexico, a test bed test of speed harmonization again showed that mobility was not improved due to sign visibility problems from sun glare and resulting high average speeds.

By deploying all three applications together, they can collectively build off the benefits of each other to provide greater levels of efficiency. One of these interactions is how CACC creates a mechanism for SPD-HARM to harmonize traffic flow and reduce speed variability between vehicles.

KEY OUTCOMES

Key outcomes of this research are:

- For speed harmonization to be effective, signs must be clearly visible.
- Speed Harmonization does not perform well if there is a breakdown formation, although hard shoulder usage combined with speed harmonization can delay the breakdown.
- Queue warning sign locations are important to its effectiveness.

[45] https://rosap.ntl.bts.gov/view/dot/3380

- Because conditions can change too fast for humans to constantly adapt to by reading warning signs, automation is the key moving forward.
- When using variable speed limits, high speed compliance depends on the driver's perception of safe speeds
- CACC systems should utilize dynamic reaction times for their car-following models.

ASSESSMENT OF INNOVATIVE AND AUTOMATED FREIGHT STRATEGIES AND TECHNOLOGIES--PHASE I FINAL REPORT

RESEARCH OVERVIEW

This report addresses how Texas Department of Transportation (TxDOT) and local transportation planners plan for freight movement strategies and what technology applications will be used to make sure that commercial deliveries travel on time efficiently. To do so, it identified a process to evaluate freight operational challenges and the different technology applications, as well as over 50 freight strategies to determine their feasibility. Each project was envisioned as a three-phased project, where Phase 1 is conceptual and explores the ideas, Phase 2 is the testing stage, and Phase 3 is the implementation stage.

RELEVANCE TO CTCS RESEARCH

A few areas of interest for research on commercial trucks in relation to the extent of CAV research and applications to promote mobility between intersections and adjacent freeway/ramp/arterial networks are autonomous and driverless truck technologies, and other corridor improvement strategies using V2V and V2I technologies. These applications are as follows:

- Truck Platooning- This application uses CACC, radars, and V2V between trucks to properly maintain a constant gap as they travel a corridor. Specifically, they investigated six V2V applications: intersection-movement assist, forward-collision warning, emergency electronic brake light, blind-spot warning/lane-change warning, bridge height information, and curve-speed warning.
- Automated and Driverless Trucks- As an extension of platoons, automated and driverless trucks can help improve travel times and better maintain headway space and coordinated travel behaviors.
- Ramp Metering- The ramp metering system would improve traffic conditions for trucks, especially through urban areas. The benefits can be seen not only on the motorway, but also on parallel arterials and on the whole corridor.
- Intelligent Truck Control System- This system is designed to increase efficiency of existing infrastructure and can lead to other benefits, such as reduced emissions and noise pollution, reduced congestion, and lower costs.

KEY OUTCOMES

Key outcomes of this research are:

- For Truck Platooning, they found that there needs to be regulations established for the lead driver, a funding scheme must be secured for the implementation, and road infrastructure would need to be redesigned to accommodate this system.
- For Automated and Driverless Trucks, the biggest challenges are the regulatory environment, public acceptance, and liability. Also, there needs to be consideration for data security. However, there have been successful case studies, including ParkShuttle in the Netherlands which has been a successful automated shuttle that can be escalated for freight deliveries.

- For Ramp Metering, they found that implementation needs strong public engagement and awareness early on, adequate personnel and training is needed, and the appropriate algorithm and standardized algorithm is needed.
- For Intelligent Truck Control System, they found that a project coordinator is imperative due to the political jurisdictions and industries that are required to work together and fully understand the benefits. There is a successful case study done in Jordan with the help from the U.S. Trade and Development Administration which used an intelligent truck control system at the Port of Aqaba which resulted in reduced congested, 20% lower inland transport costs, and 5,000 tons less carbon emissions annually.

PAVING THE WAY FOR AUTONOMOUS AND CONNECTED VEHICLE TECHNOLOGIES IN THE MOTOR CARRIER INDUSTRY[46]

RESEARCH OVERVIEW

This report investigates the adoption of CAV technology in the motor carrier industry under the assumption that it is the first industry to widely adopt automation. While the technology is still early in testing, the ultimate benefits include improved driving efficiency, improved driver health and wellness, and reduced unsafe driving. The study analyzed large truck crash data between 2013 to 2015 from Missouri to understand the cause of incident and distribution.

RELEVANCE TO CTCS RESEARCH

Although the research stems from Missouri data, it is still important to understand the lessons learned from this study, especially in application to other states/ municipalities that have similar legislation, socioeconomic backgrounds, etc.

KEY OUTCOMES

Key outcomes of this research are:

- AVs and CVs are still far from having an established timeline of being developed and it's difficult to predict what technologies and steps will be involved.
- Research conclusions from one state need to be considered in context of legislation, regulations, and other complications found in other states. The same outcomes may not apply.
- The introduction of CAV in Missouri can lead to a reduction of up to 117-193 severe crashes a year.

FRATIS CONCEPT OF OPERATIONS: ASSESSMENT OF RELEVANT PRIOR AND ONGOING RESEARCH AND INDUSTRY PRACTICES

RESEARCH OVERVIEW

Building off the Concept of Operations written for the Functional Requirements for a Freight Advanced Traveler Information System (FRATIS), FHWA investigated past research efforts and testing in this report to provide a

[46] https://rosap.ntl.bts.gov/view/dot/36103

baseline assessment of where the current state of the practice is. This includes both public and private agency programs and projects, and it breaks the relevant technologies into 7 different groups. These groups include Real-time Reliable Information for Freeways, Port/Terminal Regions, and Major Freight arterials; Planning, Dynamic, and Regulatory Route Guidance; Weather Information; Terminal Queue Status; Appointment Status; Public-Sector Data Output – Performance Measures; and Container Load Matching. Based on these findings, it then establishes performance goals and measures for FRATIS, such as improved freight travel time, reduced truck trips, and reduced terminal wait times.[47]

RELEVANCE TO CTCS RESEARCH

Pertaining to CTCS, the FRATIS report considers case study applications of technologies that impact other modes of transportation. Real-Time Reliable Information for Freeways, Port/Terminal Regions, and Major Freight Arterials encompasses technologies such as:

- The Crosstown Improvement Project (C-TIP) tracks data such as traveler information, dynamic routing, and drayage optimization to optimize intermodal transfers between railroads in Kansas City
- Connected Vehicle Research is a USDOT sponsored initiative to use interoperable networked wireless communications between vehicles, infrastructure, and passengers' personal communications devices. This research will impact what type of wireless technology will be required on trucks to support V2V and V2I applications.
- SmartPark and I-5 Smart Truck Park provides trucks drivers with real-time parking information to help manage fatigue and improve driver productivity.
- State and Local Traveler Information Systems with Freight Components provides trucks with freight specific resources and could be tailored to improve efficiencies on certain corridors.
- TransCore Real-Time OnBoard Vehicle Reporting uses a GPS/Global System for Mobile (GSM) communication system for fleet management and can provide drivers with a real-time fleet communication platform. This in turn can help improve driving efficiency and safety.

Planning, Dynamic, and Regulatory Route Guidance encompasses technologies such as:

- TomTom Truck-Specific Navigation, INRIX 3rd Generation Routing, NAVTEQ Truck Routing, and Google Maps Navigation provide trucks with optimized routing pathways. Unfortunately, one of the limitations of this type of system is the type of data that is captured.
- Qualcomm In-Cab Navigation, Rand McNally IntelliRoute, Teletrac, Garmin, and PC Miler use GPS and software packages to dynamically route paths for trucks in real time.

Terminal Queue Status encompasses technologies and applications such as:

- Washington State DOT International Data Linkages Freight ITS Study which examines the deployment of congestion management systems. This provides a source of data for planners to examine to better understand queueing.
- Sensys Networks Queue Detection Systems which uses wireless, in-ground sensors to track data metrics like traffic queue, volume, and speed.
- Freeahead Bluetooth Queuing and Vehicle Detection System which uses Bluetooth devices to calculate travel and wait times.

KEY OUTCOMES

Key outcomes of this research are:

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[47] https://rosap.ntl.bts.gov/view/dot/3463

- A lot of the technologies are being outpaced in terms of development by the private sector. Thus, FRATIS needs to leverage these resources and work in tandem with the private sector when developing their processes.
- Further research needs to be conducted on communication technologies to see what is the most appropriate to be required for all trucks.

CONNECTED VEHICLE IMPACTS ON TRANSPORTATION PLANNING- TECHNICAL MEMORANDUM #2: CONNECTED VEHICLE PLANNING PROCESSES AND PRODUCTS AND STAKEHOLDER ROLES AND RESPONSIBILITIES[48]

RESEARCH OVERVIEW

This 2015 technical memorandum produced by Cambridge Systematics for USDOT discusses further application and integration of CVs in the transportation planning process and products used by agencies throughout the country. As an example, for short-range transportation plans, the report found that past issues stemmed around DSRC investment and prioritization of TSMO priorities, such as ramp metering. Also, it is noted that there is interest in how operational strategies and ITS can be used in conjunction with CV (CV) technologies to deal with arterial management. As such, agencies are currently collecting probe data from arterial corridors using Bluetooth technology or private firms and are considering installing DSRC on corridors to support programs such as Integrated Corridor Management (ICM). Other findings include how ICM can balance traffic between freeways and arterials, how Dynamic Message Signs (DMS) can be used to guide vehicles, and how advanced software has led to less expensive deployment of adaptive signal control. These efforts should be integrated into short-term plans such as the Transportation Improvement Programs (TIP) or the State Transportation Improvement Programs (STIP). Because of the complexity of comparing different elements of CAV deployment, this report focuses on documenting and organizing these elements, such as project types, involved activities, tools, products, stakeholders, and timeframes.

RELEVANCE TO CTCS RESEARCH

This found that a lot of agencies and pilots, such as Arizona DOT and the Safety Pilot Program at University of Michigan Transportation Institute (UMTRI), are deploying Dedicated Short-Range Communications (DSRC), which can help track travel times and provide a better understanding of the arterial traffic behaviors. Moreover, while certain applications can be effective at low market penetration rates, others will need a larger penetration rate to see the benefits, which will thus take longer to fully develop. Thus, applications that provide data such as physical road condition and weather performance will be developed sooner since they can be tested without having a high concentration of CVs on the streets.

Moving forward, there is an increasing need to satisfy the skill sets required to analyze data sourced from connected and automated vehicles and will require data scientists to manage the databases. This can mean multiple options, although there are arguments as to whether the public or private sectors will become a key player in these fields. In addition, new stakeholders will ultimately develop, such as cyber security, that agencies will need to develop relationships with.

KEY OUTCOMES

Key outcomes of this research are:

[48] https://rosap.ntl.bts.gov/view/dot/3558

- Agencies need to create a well-developed business case for politicians, board members, the public, and other stakeholders so that they are aware of costs and benefits.
- There is a Performance-Based Planning and Programming Guidebook that can be used for determining what performance measures are appropriate for a given CAV application
- There are currently testbeds, such as several freeways and arterials in Michigan, TxDOT owned managed lane, university owned facilities, etc., where DSRC equipped vehicles and RSE are already deployed and being tested. This can be used by planners to get a baseline understanding of what requirements may be needed in the future.

LONGITUDINAL CONTROL FOR MENGSHI AUTONOMOUS VEHICLE VIA GAUSS CLOUD MODEL

RESEARCH OVERVIEW

For an AV, it uses both longitudinal and lateral controllers, which help control the acceleration and steering of the vehicle respectively. This research investigates the use of longitudinal control with respect to the safety and stability of AV controls using longitudinal control algorithm. Through controlling the acceleration, the longitudinal controller can then also control the vehicle's headway gap between surrounding vehicles and braking for emergency situations.

- Current research on longitudinal control can be broken down into three areas:
- Longitudinal control algorithm based on rule model
- Longitudinal control algorithm based on nonlinear theory and algorithm
- Longitudinal control algorithm based on artificial intelligence algorithm

RELEVANCE TO CTCS RESEARCH

Longitudinal control is imperative to operating CAVs safely and efficiently and for them to maximize throughput in traffic flows. By optimizing the algorithm used to control the vehicle's accelerations, there are numerous side benefits that can come from this, such as reduced emissions, lower fuel consumption, and ultimately decreased congestion. While not identified in this paper, CV technology could provide additional data to the algorithm

KEY OUTCOMES

Key outcomes of this research are:

- These different algorithms for longitudinal control need to be fully tested in the real-world conditions to see if the findings match the theoretical results.
- The research findings are limited by the small sample pool of data available to back test the algorithm against.
- The algorithm is open to optimization through considering lateral controls as well.

USING COOPERATIVE ACC TO FORM HIGH-PERFORMANCE VEHICLE STREAMS

RESEARCH OVERVIEW

This report considers the impact that CACC can have on traffic flow, capacity, and throughput improvements in the freeway traffic stream through CACC vehicle string operations. Using simulations, the research tests various market penetrations, CACC managed lane (ML) strategies, a vehicle awareness device (VAD) strategy, and discretionary lane change (DLC) restrictions on the traffic on a 4-lane freeway section and a 13-mile freeway corridor. Although CACC is generally agreed to improve traffic where implemented, it is hard the quantify the degree of benefits achieved through this implementation without a large-scale field test is performed with a significant portion of the fleet equipped with CACC. Thus, to address this, the study is broken into two objectives:[49]

1) Provide a realistic estimation of the impacts of CACC on freeway highway capacity and throughput
2) Determine the CACC operation strategies that create the most capacity and throughput improvement on the freeway traffic system

RELEVANCE TO CTCS RESEARCH

Because past literature review has shown that ACC alone has little effect on lane capacity and cannot achieve string stability, it is important to the CTCS research to research the capabilities of CACC strategies. Moreover, there is little research done to understand their impact on highway capacity and throughput in a complicated multi-lane freeway environment. This research helps to mitigate that gap through creating a traffic simulation platform that can test these strategies through capturing and modeling human drivers' behaviors, CACC drivers' behaviors, and the interaction of the two driver groups. Thus, it creates a platform for future studies to work off to either test their own strategies, incorporate improved behavior modeling, or include other technologies in conjunction with CACC, such as speed harmonization and automated merging or lane changing assistance.

KEY OUTCOMES

Key outcomes of this research are:

- For homogenous freeway segments and freeway on-ramp merging areas, increasing CACC market penetration led to a quadratic increase in pipeline capacity. However, this improvement decreases for the on-ramp merging area as on-ramp traffic increases
- ML and CAV strategies are most beneficial in low/medium CACC market penetration conditions for maintaining CACC string stability
- The DLC strategy has the greatest benefit in high CACC market penetrations conditions
- For the State Route-99 testing site, there is a critical CACC market penetration of 20-40%

[49] "Using Cooperative ACC to Form High-Performance Vehicle Streams." National Automated Highway Systems Consortium | California PATH. Accessed January 28, 2019. https://path.berkeley.edu/research/connected-and-automated-vehicles/using-cooperative-acc-form-high-performance-vehicle.

VEHICLE-TO-VEHICLE (V2V) COMMUNICATIONS FOR SAFETY

RESEARCH OVERVIEW

The USDOT Intelligent Transportation Systems Joint Program Office created a V2V safety research program with the goal of addressing 4 objectives:

- Developing a V2V active safety application for the most critical crash scenario
- Developing a safety benefits estimation for the 2013 National Highway Traffic Safety Administration (NHTSA) agency decision
- Working with the industry to improve safety benefits for V2V-equipped vehicle owners
- Complete testing of V2V communications technologies and standards[50]

RELEVANCE TO CTCS RESEARCH

To achieve these goals, they've identified eight tracks to conduct their V2V research needs that will address scenarios where automobiles interact with trucks, buses, and trains. From this, they will work with stakeholder groups to ensure that the appropriately crucial technologies for safety are developed between the respective groups and deployed.

KEY OUTCOMES

Key outcomes of this research are:

- Revisions to message (SAE J2735) and security (IEEE 1609.2 and IEEE 1609.3) standards are critical.
- The Safety Pilot Experimental plan was created, which uses calculations to ensure that enough data is collected through the necessary amount of interactions for safety benefit estimations.
- Some V2V applications require a redundant sensor for reliability.

INTELLIGENT TRANSPORT SYSTEMS (ITS); VEHICULAR COMMUNICATIONS; BASIC SET OF APPLICATIONS; PART 3: SPECIFICATIONS OF DECENTRALIZED ENVIRONMENTAL NOTIFICATION BASIC SERVICE

RESEARCH OVERVIEW

The European Telecommunication Standards Institute (ETSI) has developed the Basic Information Message, Decentralized Environmental Notification Message, and the Cooperative Awareness Message, which are used in an environment of connected devices.[51]

[50] "Vehicle-to-Vehicle (V2V) Communications for Safety." Intelligent Transportation Systems - Automation. Accessed January 28, 2019. https://www.its.dot.gov/research_archives/safety/v2v_comm_progress.htm.

[51] http://www.etsi.org/deliver/etsi_ts/102600_102699/10263703/01.01.01_60/ ts_10263703v010101p.pdf

RELEVANCE TO CTCS

- Basic Information Message (BIM) - BIM is a proposed new message format that enables the transmission of all required data elements for V2I safety applications in a single message and is extensible to support future event-based applications. This concept of message structure uses existing SAE J2735 data elements.
- Decentralized Environmental Notification Message (DENM) - Provides information regarding thirteen use cases: emergency electronic brake light, wrong way driving warning, stationary vehicle – accident, stationary vehicle – vehicle problem, traffic condition warning, signal violation warning, road work warning, collision risk warning, hazardous location, precipitation, road adhesion, visibility, and wind.
- Cooperative Awareness Message (CAM) - Information of presence, positions as well as basic status of communicating ITS stations to neighboring ITS stations that are located within a single hop distance. Includes vehicle position and vehicle basic data (acceleration, path history, curvature, vehicle size etc.). Supports 32 use cases in four application classes including active road safety (e.g. emergency vehicle warning), cooperative traffic efficiency (e.g. regulatory speed limit notification), co-operative location services (e.g. parking management), and global internet services (e.g. insurance and financial services)

KEY OUTCOMES

It is important to consider standardized messages that are used in other CV systems to determine if they could be useful for CTCS. Understanding ETSI messages (which are used predominately in Europe) may be useful for determining which standardized messages should be used to enable CTCS use cases should they be similar in nature a use case that has already been implemented in Europe.

C-ROADS[52]

RESEARCH OVERVIEW

The C-Roads platform kicked off in October 2016 and brings together authorities and road operators to harmonize the deployment activities of C-ITS across Europe. Pilot Sites in 16 core countries will deploy a C-ITS platform to enable Day 1 services.

RELEVANCE TO CTCS

Because this project is currently ongoing, there are not specific outcomes that are currently available and can be applied to CTCS.

KEY OUTCOMES

Highly-beneficial C-ITS services should be deployed quickly so that end-users and society at large can benefit from them as soon as possible. This early deployment list is defined below:

- Slow or stationary vehicle(s) & traffic ahead warning;
- Road works warning;
- Weather conditions;

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[52] "C-Roads - The Platform of Harmonised C-its Deployment in Europe." Platform: C-Roads. Accessed January 28, 2019. http://www.c-roads.eu/.

- Emergency brake light;
- Emergency vehicle approaching;
- Other hazards.
- Signage applications:
- In-vehicle signage;
- In-vehicle speed limits;
- Signal violation / intersection safety;
- Traffic signal priority request by designated vehicles;
- Green light optimal speed advisory;
- Probe vehicle data;
- Shockwave damping (falls under ETSI category 'local hazard warning').

In a second phase, the Day 1.5 C-ITS services list would be deployed. This is a list of services for which full specifications or standards might not be completely ready for large scale deployment from 2019, even though they are generally mature.

- Information on fueling & charging stations for alternative fuel vehicles;
- Vulnerable road user protection;
- On street parking management & information;
- Off street parking information;
- Park & ride information;
- Connected & cooperative navigation into and out of the city (first and last mile, parking, route advice, coordinated traffic lights).

INTERCOR

RESEARCH OVERVIEW

Interoperable Corridors (InterCor) is a European project which aims to connect the C-ITS corridor initiatives of the Netherlands C-ITS Corridor (Netherlands-Germany-Austria), the French corridor defined in the SCOOP@F project, and the United Kingdom and Belgian C-ITS initiatives.[53][54]

RELEVANCE TO CTCS RESEARCH

InterCor is currently ongoing. Due to limited information on other C-ITS services, it is unknown if any of the outcomes of this project will be applicable to CTCS use cases. Future documents that discuss the outcomes of this project will be used in the development of CTCS use cases, if available when use cases are being developed.

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[53] http://intercor-project.eu/

[54] http://intercor-project.eu/wp-content/uploads/sites/15/2017/06/Cooperatieve-ITS-Corridor-Description-of-the-System-Concept-Final_v1.0-20160704.pdf

KEY OUTCOMES

- Road Works Warning - RWW aims at reducing the number of collisions with safety-objects near road works. RWW will alert the road user when approaching a dangerous zone and will simultaneously provide information on the changes in the road layout.
- Probe Vehicle Data - Improve insight on the traffic situation by collecting sensor-data (such as speed and direction) transmitted by passing vehicles. PVD will improve information on actual traffic behavior and status, enabling the road operator to improve traffic management.
- Collision Risk Warning – Transmitters installed on traffic inspector's vehicles send a signal to a central system when positioned at a dangerous location. The central system sends alerts to passing vehicles by means of conventional media.

Table 10 provides a list of services that will be deployed at each test site:

Table 10: C-ITS Services

C-ITS Services	Netherland	France	Belgium	UK
In-Vehicle Signage	X	X	X	X
Probe Vehicle Data	X	X		X
Road Work Warning	X	X	X	X
Green Light Optimal Speed Advice	X	X	X	X
Multimodal cargo Transport Optimization	X	X	X	
Green Light Optimal Speed Advice	X	X		
Tunnel Logistics	X		X	