Connected-Autonomous Traffic Signal Control Algorithms for Trucks and Fleet Vehicles

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1. Introduction

Connected vehicle (CV) technologies enable vehicles to exchange information with each other (vehicle-to-vehicle [V2V]) and with the roadside infrastructure (vehicle-to- infrastructure [V2I]) in real time (*ITS JPO, 2018a*). The CV systems combine different technologies, such as wireless communications, advanced vehicle sensors, advanced roadside infrastructure, onboard computers/processing and similar. Automated vehicles (AV) use various technologies (radar sensors, LiDar, GPS and similar) to sense their surroundings and take driving functions from the driver at different levels (*ITS JPO, 2018b*). The connected-automated vehicles (CAV) integrate the functions of CVs and AVs for a greater benefit, as shown in Figure 1. The US DOT recognizes several areas of CAV technology applications, such as V2I safety, V2V safety, road

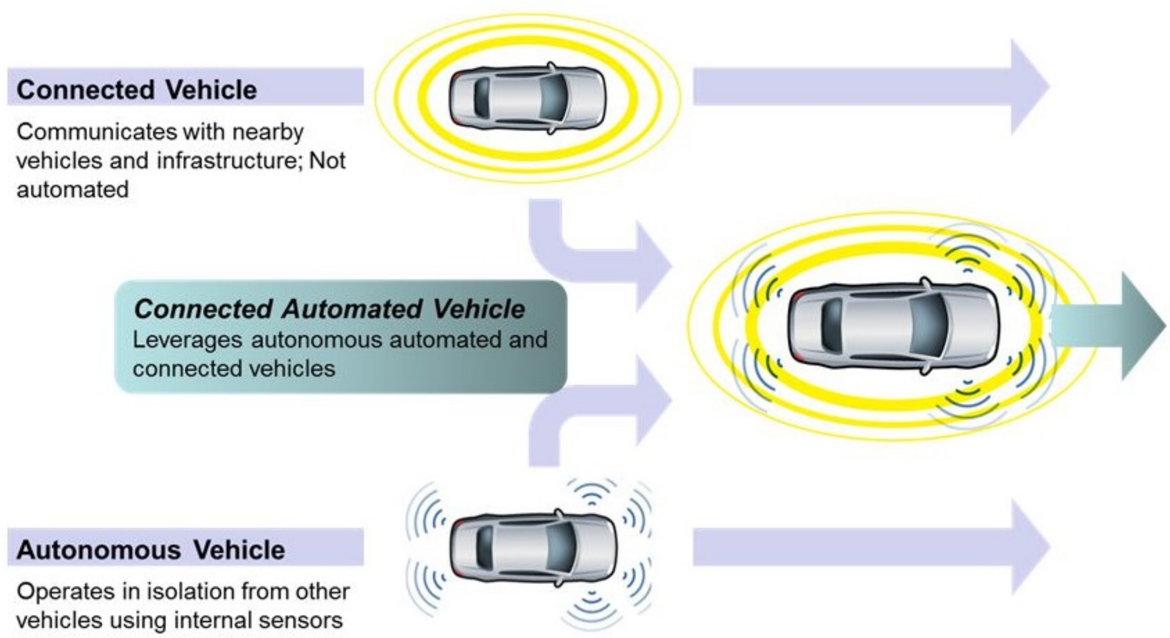

Figure 1: CAVs (Source: USDOT)

weather, environment and mobility, among others (*ITS JPO, 2018c*).

Traffic control signals assign the intersection right-of-way to various traffic movements and transportation modes, temporally separating the conflicting ones. Actuated traffic control signals use vehicle detection and preset signal timing parameters to adjust their operation to changing demand. They also introduce special operations for emergency, transit and freight vehicles. These operations can provide certain level of priorities for these vehicles, reducing the delay and improving safety. However, the traditional detection and communication technologies have been based on lower fidelity detection and less intelligent control techniques. The CAV technology offers new venues for detection, communication and decision algorithms based on the wide array of information being shared among vehicles, infrastructure and control devices.

WYDOT is in the process of upgrading traffic signals and installing CAV hardware and software. This creates opportunities for developing intelligent control strategies that would improve traffic operations and safety, further leading to better sustainability and helping the economic development. All roadway facilities in Wyoming experience high percentages of heavy truck traffic. Because of their physical dimensions and maneuvering capabilities, they significantly impact operations, and have prominent effects on safety. Furthermore, the efficiency of freight transportation is of a high economic importance. Therefore, strategies that improve truck operations and safety in all environments are of great significance for Wyoming conditions. Similar priority strategies can be implemented for transit vehicles. Through CAV technologies, the possibilities for adaptive Transit Signal Priority (TSP) are numerous. A transit vehicle's location, speed, heading, occupancy, schedule adherence, as well as its physical characteristics, can be communicated in real time, allowing for the selection of priority strategies that would benefit the transit vehicle, without impacting other traffic. Although Wyoming cities do not have highly developed transit systems, certain transit and shuttle programs can benefit from the TSP implementation, such as for example Jackson Hole's START Bus. Traffic operations and safety applications that can greatly benefit from the CAV technologies are parts of the USDOT's Dynamic Mobility Applications (DMA) research plan and have a high level of national importance.

2. Problem Statement

The standards and protocols of CAV technologies are currently in development, with limited number of tests and implementations. The installation of CAV hardware/software in traffic signals in Wyoming creates opportunities for developing methods and algorithms that would help the State's unique transportation challenges. ConnexUs Lear CV hardware will first be installed at six signalized intersections near freeway interchange ramps in Evanston, Rock Springs, Rawlins, Laramie and Cheyenne. This study will review the current protocols and recommend options applicable to Wyoming conditions. It will analyze, assess and develop traffic control algorithms that would use CAV technologies to improve operations and safety through signalized intersections. The focus will be on optimizing operations of freight and fleet (snowplows and striping) vehicles through signalized intersections. The analyzed strategies will include queue warning, speed harmonization and freight priority. Other strategies that would improve traffic operations and help transit programs in high-traffic areas of Wyoming cities, on the example of Jackson Hole, will also be assessed for future implementation. The developed control algorithms will be tested in a virtual environment (through traffic microsimulation and driving simulation) and the recommendations for field implementation will be provided to WYDOT. The researchers will work closely with WYDOT engineers to develop control protocols that would have significant practical applications. The programs will be tested on the six signalized intersections, but the transferability to other locations will also be explored. Furthermore, because of the importance of these technologies on the national level, this study will benefit transportation agencies across the U. S., especially those that face similar transportation challenges.

3. Background

CAV technologies are gaining a momentum in research and practice. The benefits of these technologies are just beginning to be recognized. The limited number of field tests have proven that they can be used for different adaptive traffic control programs. There are still many areas that need to be covered through research. CAV applications that are directly related to the proposed study are defined in the USDOT CV applications for mobility as following (*ITS JPO, 2018c*):

- Intelligent Traffic Signal System (ISIG)
- Queue Warning (Q-WARN)
- Dynamic Speed Harmonization (SPD-HARM)
- Freight Signal Priority (FSP)
- Transit Signal Priority (TSP)

The following section describes the basics of the selected applications. More detailed information, implementations, tests and research results are provided in the accompanying literature review.

The Intelligent Traffic Signal System (ISIG) is using high-fidelity data collected from vehicles through V2V and V2I communications (as well as pedestrian and non-motorized travelers through mobile sensors) to control signals and maximize throughput in real time. The ISIG application also plays the role of an overarching system optimization application, accommodating transit or freight signal priority, preemption, and pedestrian movements to maximize the overall network performance (*ITS JPO, 2018c; Yang, 2017*). In a connected vehicle environment, Road Side Equipment (RSE) associated with an intersection signal controller broadcasts an intersection geometry (MAP) and signal phase and timing (SPaT) message. A vehicle with on-boar equipment (OBE) that enters the range of the RSE will receive the MAP and SPaT data and will actively broadcast basic safety messages (BSMs) (*Leonard, 2017; Cronin, 2012*). The BSM contain static and dynamic elements of the vehicle, as well as the status of various vehicle systems (e.g. brakes, doors, windshield wipers etc.). Depending on the type of the vehicle, it may send a signal request message (SRM) to request signal priority or preemption. In turn, the RSE sends a signal status message (SSM) with the acknowledgements of priority requests and the status of active priority/preemption request(s). This message exchange occurs in real time. This allows traffic signal control and signal priority for multiple modes to be managed within an integrated framework. Different levels of priority for eligible vehicles, whether multi-modal or within the same mode, can be assigned based on the local interpretation of signal priority importance and usefulness (*Cronin, 2012; University of Arizona et al., 2016*).

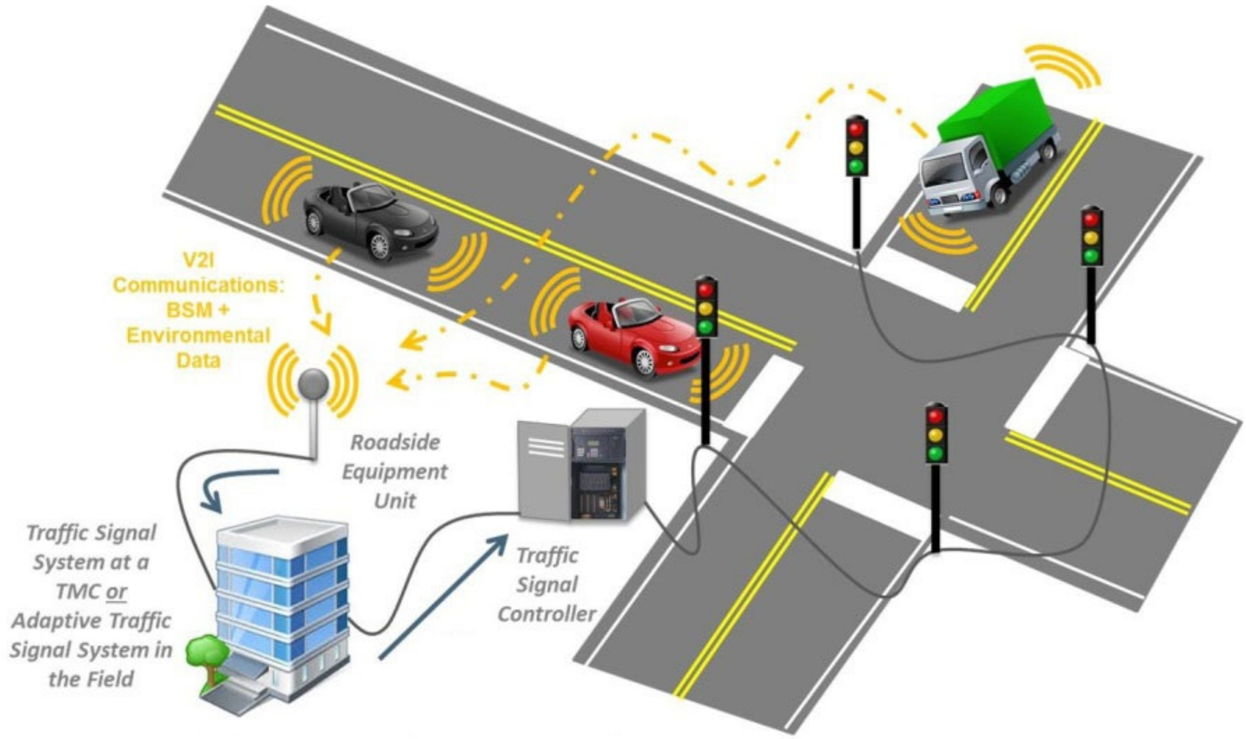

Figure 2: ISIG (Source: USDOT)

The Queue Warning (Q-WARN) application uses CV technologies to enable vehicles within the queue to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to upstream vehicles and to infrastructure. The queue warnings is sent to oncoming vehicles to prevent rear-end or other secondary collisions. The Q-WARN application performs two essential tasks: queue determination (detection and/or prediction) and queue information dissemination (*ITS JPO, 2018c*). In cases of limited visibility (either technical or environmental), the Q-WARN system can work in conjunction with the traffic controller to transmit the queue information to the vehicles approaching the intersection. This is of particular importance for heavy vehicles, due to their longer stopping distances.

Dynamic Speed Harmonization (SPD-HARM)uses the communication among vehicles to control the speeds of clustered CAVs. The objective of this application is to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions in order to maximize traffic throughput and reduce crashes (*ITS JPO, 2018c*).Speed harmonization increases the capacity of traffic facilities and reduces congestions due to the phantom traffic jam effects. It also allows creating and maintaining vehicle platoons, increasing mobility through signalized intersections. The signals communicate their status (through SPaT) and the clustered vehicles will respond by adjusting and harmonizing their speeds so that the platoon reaches the signal during the green phase time.

Freight transported by trucks within the US exceeds 10,000 millions of tons per year, equaling to more than $11,000 billion (*Bureau of Transportation Statistics, 2018*). Fast and on-time freight delivery is of outmost economic importance. Majority of freight flows at their origins or destinations travel through urban areas. Certain parts of urban networks, such as industrial, warehouse or port areas, experience high volumes of truck traffic. Large trucks have significantly different physical characteristics from passenger cars, requiring more space and time for maneuvers. Therefore, the operation of traffic signals along truck routes can be modified to give certain priority for trucks, called Freight Signal Priority (FSP). This priority allows extra time for trucks to clear the intersection without stopping, or an earlier return to green phase if the truck is stopped, improving their travel time reliability and enhancing safety. Having trucks at the front of the queue is an undesirable scenario, since the start up lost time for all vehicles is greater, and the vehicles behind have limited visibility of the traffic control devices. The benefits of FSP include, but are not limited to, reduced truck stops and delays, a reduction in truck red-light running, safer phase termination for trucks, higher capacity due to the reduced start-up lost time and similar (*Signal Timing Manual, 2015*). Since more information is being transmitted through CAV communication channels, the signal controller receives more data that can be used to adjust the operations. Therefore, additional strategies to FSP might include dynamic yellow/red clearance intervals (to allow more time for large vehicles or slow moving vehicles to clear the intersection before moving onto the next signal phase), adaptive left-turn treatments and operations (for example not allowing permitted a left turn if certain large vehicles are waiting in the left turn lane and the oncoming traffic volumes are high), or adaptive ring-barrier structure and sequence, that can change the order of phase sequences as needed. These additional strategies can have significant safety benefits, in addition to improving operations.

Transit Signal Priority (TSP) facilitates the movement of in-service transit vehicles through signalized intersections. Different strategies, such as green extension, early green, phase rotation, phase insertion and similar are used for this purpose. The traditional TSP uses wireless communication (radar or infrared) between the transit vehicle and the traffic signal. However, the CAV technology will allow for sharing more information between the systems and providing opportunities for adaptive priority. This TSP can utilize the vehicles' position and speed, occupancy, schedule, door status and other information contained in the BSM to adjust the signal operation and select the optimal strategies that would benefit the transit vehicles, without impacting other traffic.

The standards and protocols of CAV technologies are currently in development, with limited number of implementations. The installation of CAV hardware/software in traffic signals in Wyoming creates opportunities for developing methods and algorithms that would help the State's unique transportation challenges (primarily high heavy truck traffic and adverse weather). This study will review the current protocols and recommend options applicable to Wyoming conditions. The focus will be on optimizing operations of freight and fleet vehicles through signalized intersections. The six signalized intersections with CV hardware will be used as test-cases, and the appropriate algorithms will be created and tested. The study will also use high-fidelity traffic microsimulation, with CAV and traffic control emulators, as well as driving simulation, which would help develop field-ready control programs.

4. Study Objectives

The goal of the study is to create field-ready, CAV-based traffic control programs that will improve operations and safety of trucks and fleet vehicles. The main research objectives of this study are as follows:

Objective 1: *Synthesize the current state of research and practice related to signal control programs under the CAV environment*

The study will provide an up-to-date review of current literature and practice related to the CAV signal control and related algorithms. The focus will be on the ISIG, Q-WARN, SPD-HARM and FSP, but also other mobility and safety applications will be reviewed and summarized, such as TSP. The review will help the research team in developing and testing control programs proposed in this study.

Objective 2: *Create intersection communication protocols for CAV implementation suitable for Wyoming conditions*

The first step in WYDOT's CAV signal deployment would be creating protocols for communication based on the ConnexUs Lear hardware and software. These protocols also need to conform to the national standards. For each intersection with the CAV technology, the intersection geometry needs to be created in the MAP format. This is an ASCII text file which contains intersection map data which establishes points for each lane and element. Both MAP and SPaT communication need to comply with the SAE J2735 standard. Installing CAV technologies and developing MAP/SPaT communication can also help WYDOT with the SPaT challenge.

Objective 3: *Develop and test algorithms for ISIG, Q-WARN, SPD-HARM and FSP*

This will be the main objective of the study. The control algorithms will be developed based on the needs and the current state of practice, as well as the local conditions and needs. One of the main goals will be to create control programs that can be implemented in the field. The focus of the algorithms will be to improve traffic operations, as well as create traffic conditions that will benefit safety. The research team will use traffic microsimulation (VISSIM with the traffic control software-in-the-loop [SIL] capabilities) and the UW driving simulator (passenger car and truck) to test and improve the control programs. In collaboration with WYDOT, selected programs may be implemented and tested in the field. The research team proposes to develop and test algorithms for trucks and fleet vehicles for two reasons. First, high truck traffic volumes in Wyoming create many operational and safety concerns, and the efficiency and safety of snowplows and striping trucks is of great importance. Second, it is safe to assume that the trucks and fleet vehicles will be the first ones to be equipped with CAV technologies in larger numbers, providing higher penetration rate of CAV-equipped vehicles. A limited testing of TSP control programs will be performed for future implementation, using parts of Jackson Hole as test-beds.

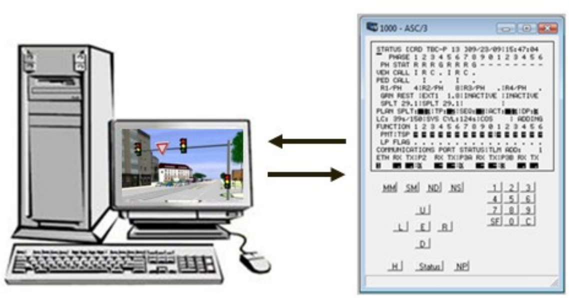

Figure 3: VISSIM with ASC/3 SIL

Figure 4: UW Driving Simulator (WYOSIM)

Objective 4: *Provide recommendations for CAV-based traffic control programs*

Once the algorithms have been tested and control programs developed, the research team will provide recommendations to WYDOT for field implementation. Based on the WYDOT needs, the team may also analyze other types of CAV algorithms.

5. Methodology

The two main parts of this study will consist of CAV-based algorithms development, and a creation of field-ready traffic control programs. The study will use the review of literature and practice, collection of the existing field data, and traffic microsimulation and driving simulation models to develop, test and select the most appropriate CAV control programs for ISIG, Q-WARN, SPD-HARM and FSP applicable to Wyoming conditions. Field data (geometries, traffic and control) will be collected from selected test-sites and used in the analysis and models development. The algorithms will be developed according to the actual standards and protocols for CAV technologies. Traffic microsimulation software VISSIM will be used extensively to develop and test actual control programs that will be field-ready, while driving simulation will be used to test the applicability of the control programs in the field.

The study will provide several expected outcomes. The first will be a synthesis of existing literature and practice on CAV technologies and algorithms, with a focus on traffic signal operation. The literature review will recognize the current state of research and practice, technologies, implementations and potential gaps and problems that need to be addressed in the future. The second outcome will be a set of microsimulation models for selected locations, that can also be used in future research. The models will use state-of-the-art software and traffic control programs through SIL implementation. The modeling process will be described in detail for future references and similar uses. The most important outcome of the study will be a set of field-ready traffic control algorithms and programs that use CAV technologies to optimize operations of freight and fleet vehicles through signalized intersections and urban arterials. This research would not be beneficial only for WYDOT and Wyoming agencies, but also for agencies across the U.S. that are preparing for the era of CAV technologies. The research will also represent an excellent starting point for special signal operations using connectivity technologies.

6. Study Tasks

The work plan is divided in seven tasks and developed for a two-year performance period. The tasks are as follows:

Task 1: Review of literature and practice related to CAV technologies and operations (NTP – Month 3, and updated throughout the study)

The review will include existing standards and protocols, hardware and software, operational and safety methodologies, and CAV implementations and testing. The literature review will also provide some recommendations for the selection of test cases, methodologies, testing and results interpretation.

Task 2: Data collection (Month 3 – Month 9)

The research team will identify the traffic data needed for the research, and the existing data sources. The data collection will be performed for the six test sites. The data will include geometrical characteristics, operational characteristics (traffic volumes, traffic composition) and traffic control data (traffic signal timings and roadway/intersection signage).

Task 3: Development of traffic simulation models (Month 6 – Month 12)

The research team will create and calibrate traffic microsimulation models for the selected locations. The models will be developed in PTV VISSIM software with traffic signal control emulators and used to test CAV algorithms. Selected locations out of the six sites will be recreated in a driving simulator to test the applicability and response to the traffic control programs.

Task 4: Development of CAV protocols, algorithms and control programs (Month 9 – Month 15)

The focus of the CAV algorithms will be on ISIG, Q-WARN, SPD-HARM and FSP. The reason for this is two-fold: first, Wyoming experiences high heavy truck volumes, so these applications will be very beneficial for local conditions; and second, it is more likely that trucks and fleet vehicles will be the first to be equipped with CAV technology. The FSP algorithms will not be focused on priority only, but will also include other strategies such as dilemma zone protection, dynamic yellow/red clearance intervals, adaptive left turn treatments and operations, adaptive ring/barrier structure and phasing, and similar.

Task 5: Testing of CAV algorithms and control programs (Month 12 – Month 20)

The initial tests of algorithms and programs will be performed in microsimulation. Different scenarios will be developed by upgrading the base models, and the algorithms will be implemented through VISSIM's CAV external driver modules and software-in-the-loop (SIL) traffic controllers using logic processors. Selected locations and programs will be selected for driving simulation, and will be recreated and tested in a driving simulator to assert their effectiveness and drivers' response. In collaboration with WYDOT, some programs may be selected for field testing once the needed equipment is installed.

Task 6: Providing recommendations for field implementation (Month 20 – Month 22)

Through microsimulation and driving simulation testing, the most promising programs will be selected and recommended for field implementation. The recommendations will include detailed descriptions of algorithms' operations and implementation steps.

Task 7: Final report (Month 20 – Month 24)

The research team will summarize the study in a formal final report. Technical reports and memos will be developed throughout the study. The final report will be a complex document that include the review of literature and practice, algorithms, models, testing procedures, results and recommendations.

Figure 5 shows the study methodology and relationships between study objective and study tasks. The timeline of the study is presented in Figure 6.

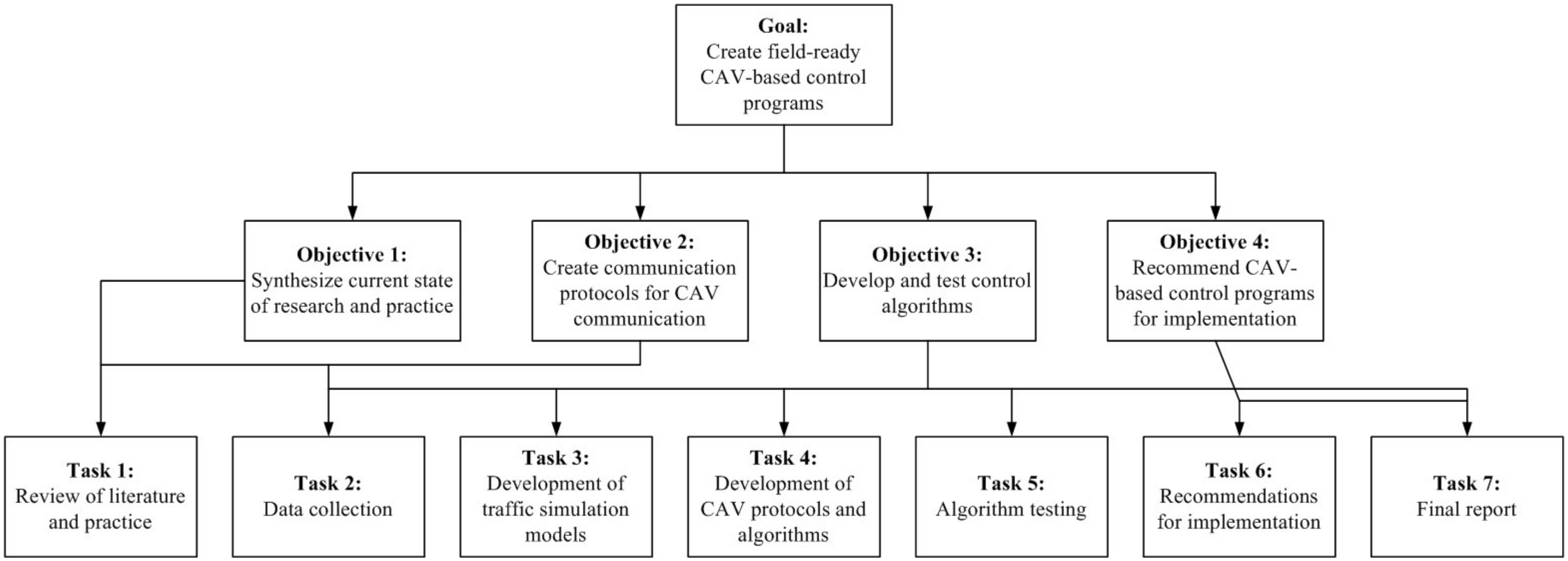

Figure 5: Study Methodology

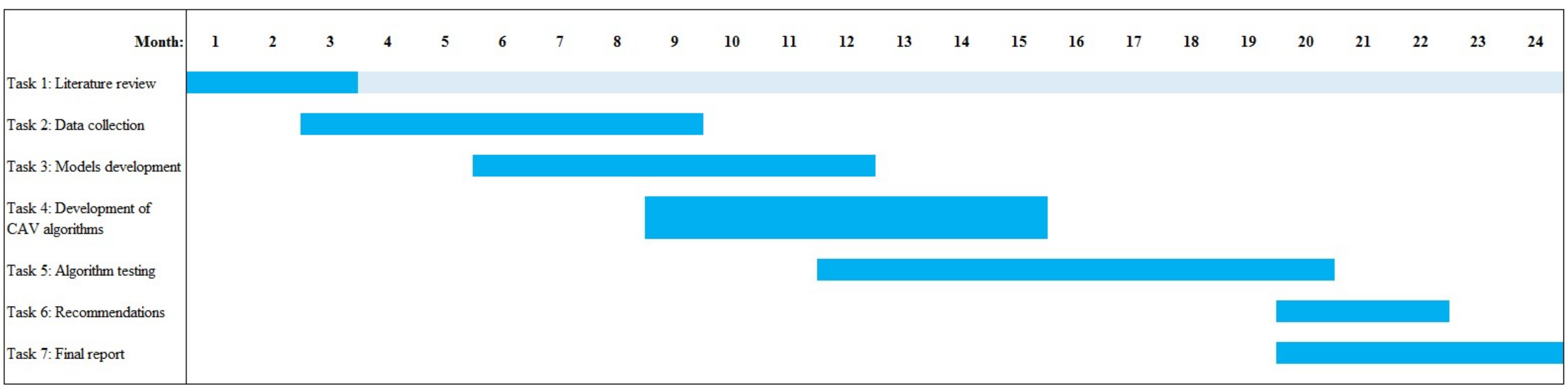

Figure 6: Study Timeline

7. Timeline and Staffing

The study will be performed in 24 months after the Notice to Proceed (NTP). Progress reports will be submitted to WYDOT at predetermined intervals. A final report and several presentations to appropriate WYDOT personnel and other stakeholders are anticipated to take place at the conclusion of the study. Recommendations for potential mitigation strategies will be made and discussed with WYDOT.

The project will be led and supervised by Dr. Zlatkovic and Dr. Ahmed, and graduate and undergraduate students will be assigned to different tasks throughout the project.

8. Budget and Matching Funds

The requested funds from the WYDOT RAC for this study are $148,866, as shown in Table 1. WYDOT Traffic has also budgeted $42,000 for the CAV hardware to be installed at the six intersections. UW is obtaining additional $60,000 from the MPC University Transportation Center as the matching funds, and the breakdown is shown in Table 1.

Table 1: Study Budget

Categories	MPC	WYDOT RAC	WYDOT Traffic	Total
Faculty Salaries	$2,712	$35,650		$38,362
Staff Fringe Benefits	$1,174	$15,436		$16,610
Student Salaries	$22,380	$48,760		$71,140
Student Fringe Benefits	$873	$1,902		$2,775
Total Personnel Salaries	$24,880	$84,410		$109,290
Total Fringe Benefits	$1,955	$17,338		$19,293
TOTAL Salaries & Fringe Benefits	$26,835	$101,748		$128,583
Travel		$5,000		$5,000
Equipment	$11,000			$11,000
Supplies		$1,000		$1,000
Other Direct Costs (Grad student T&F, insurance)	$9,784	$19,568		$29,352
TOTAL Direct Costs	$48,058	$127,316		$175,374
F&A (Indirect) Costs	$11,941	$21,550		$33,491
CAV Hardware			$42,000	$42,000
TOTAL	**$60,000**	**$148,866**	**$42,000**	**$250,866**

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