VIRGINIA TECH TRANSPORTATION INSTITUTE

Field Demonstration of a Connected Automated Vehicle Traffic Signal Control System

Date: 3/21/2019

Partners:

Volkswagen Group of America, Electronics Research Laboratory
Traffic Technology Services, Inc.
Virginia Department of Transportation

VIRGINIA TECH TRANSPORTATION INSTITUTE

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March 21, 2019

U.S. Department of Transportation
Federal Highway Administration
ATTN: Sarah Tarpgaard, HCFA-32
1200 New Jersey Avenue, SE
Washington, D.C. 20590

Subject: Response to Automated Driving System Demonstration Grants, NOFO # 693JJ319NF00001

Dear Sarah Tarpgaard:

The Virginia Tech Transportation Institute (VTTI) is pleased to present this proposal entitled "Field Demonstration of a Connected Automated Vehicle Traffic Signal Control System," to USDOT in response to NOFO #693JJ319NF00001. This project will develop and demonstrate a connected and automated vehicle traffic signal control application along signalized arterials. In the U.S., intersection-related crashes account for over half of all fatal and injury crashes. Poorly designed or poorly traffic signal systems can contribute to higher crash rates, delays, and excess energy consumption by vehicles. The system to be demonstrated in this project is expected to simultaneously improve traffic safety, reduce traffic congestion, and increase energy efficiency.

The team assembled for this project includes experts in traffic signal systems, vehicle systems engineering, communication, system integration and implementation, research, data storage and security, and vehicle testing from the following organizations:

- The Virginia Tech Transportation Institute (lead);
- Volkswagen Group of America, Electronics Research Laboratory;
- Traffic Technology Services, Inc.; and
- The Virginia Department of Transportation (VDOT).

We look forward to working with USDOT on this important project. Please do not hesitate to contact us with any questions.

Sincerely,

Pascha Gerni
Chief Finance and Administration Officer, Virginia Tech Transportation Institute
PGerni@vtti.vt.edu

Summary Table

Project Name/Title	Field Demonstration of a Connected Automated Vehicle Traffic Signal Control System
Eligible Entity Applying to Receive Federal Funding (Prime Applicant's Legal Name and Address)	Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, Virginia 24061-0536
Point of Contact (Name/Title; Email; Phone Number)	Hesham Rakha – Samuel Reynolds Pritchard Professor of Engineering/Director of Center for Sustainable Mobility hrakha@vt.edu, 540-231-1505
Proposed Location (State(s) and Municipalities) for the Demonstration	Virginia – Blacksburg/Christiansburg and Fairfax
Proposed Technologies for the Demonstration (briefly list)	The project will develop and demonstrate a fully-integrated Connected Automated Vehicle Traffic Signal Control (CAV-TSC) system along signalized arterials using L2+ or higher automated vehicles equipped with 4G/LTE communication (L3 vehicles could be used in the final demonstration). The CAV-TSC system will be developed as a bi-level controller, with the traffic signal controller operating at the upper level, and the CAV controller running at the lower level. Feedback between the two controllers will allow each controller to benefit from the other. The system attempts to improve traffic safety in the vicinity of traffic signals and in addition reduce traffic congestion and increase vehicle energy efficiency. The team will conduct field tests using at least two L2+ or higher CAVs along a signalized arterial in the Blacksburg/Christiansburg, VA area and an arterial in Northern Virginia.
Proposed duration of the Demonstration (period of performance)	48 Months
Federal Funding Amount Requested	$3,328,708
Non-Federal Cost Share Amount Proposed, if applicable	$1,626,470
Total Project Cost (Federal Share + Non-Federal Cost Share, if applicable)	$4,955,178

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Part 1. Project Narrative & Technical Approach

Executive Summary

Automated Driving Systems (ADSs) have the potential to improve the safety of the transportation system by eliminating driver errors, enhancing traveler mobility (especially for children and the elderly) by providing a means of transportation without the need to drive, and reducing energy consumption by smoothing vehicle trajectories. Vehicle connectivity [vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I), more generally known as V2X] adds another dimension to ADSs as it expands the amount of information and improves the quality of information provided to ADSs, allowing them to make better decisions. These connected ADSs are referred to as connected automated vehicles (CAVs) in the remainder of the proposal.

Among the potential benefits of CAVs, safety is typically the number-one priority for road users. In 2017, transportation-related accidents took 39,032 lives in the U.S., of which highway crashes were responsible for the majority (37,133 lives) [1]. Of all motor vehicle crashes, 94% were caused by driver-related factors such as impaired driving, distraction, and speeding or other illegal maneuvers [2]. CAVs have the potential to significantly improve safety by reducing crashes caused by human error, thereby saving lives.

Traffic signals, which are the most popular traffic control devices, control the right of way at roadway intersections by temporally separating conflicting movements to enhance the mobility and safety of at-grade intersections. However, poorly designed traffic signal systems can result in delays, higher crash rates, and excess vehicle energy consumption. Crashes occurring at or near intersections are a major safety problem. Based on empirical data, more than 50% of all total fatal and injury crashes in the U.S. are intersection related [3]. These crashes are attributed to inadequate surveillance (44.1%), false assumptions of the actions of others (8.4%), obstructed views (7.8%), illegal maneuvers (6.8%), internal distractions (5.7%), and misjudgment of the gap or other's speeds (5.5%). In addition, poorly timed signalized intersections typically increase traffic delay by forming bottlenecks along roadways, thus increasing urban congestion. Furthermore, vehicle fuel/energy efficiency is considerably reduced at signalized intersections. A recent study found that vehicles consume 78% more fuel/energy at signalized intersections while accelerating and idling compared to typical arterial roads [4].

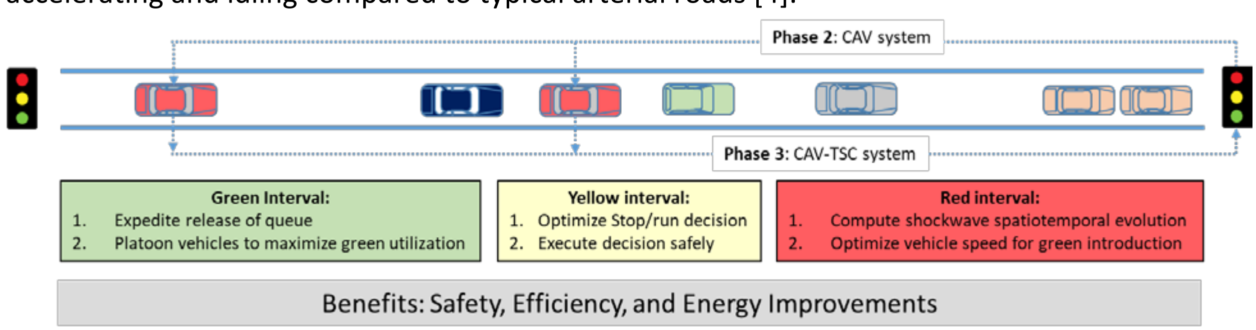


Figure 1: Proposed vehicle control along signalized arterials

The objective of the project is to develop and demonstrate a CAV and fully integrated CAV and Traffic Signal Control (CAV-TSC) application along signalized arterials, as depicted in Figure 1 (CAVs are depicted as red vehicles). The CAV-TSC system will be a bi-level controller, with the traffic signal controller operating at the upper level, and the CAV controller running at the lower level. Feedback between the two controllers will allow each controller to benefit from the other. For example, the traffic signal controller will use the CAV controller to predict vehicle arrivals more accurately and thus optimize the traffic signals using better data. Alternatively, the traffic signal controller will share its control strategy with the CAVs to improve the control strategies by accounting for future changes in the traffic signal timings. The system aims to improve traffic safety while at the same time reduce traffic congestion and increase vehicle energy efficiency. Traffic safety is enhanced as follows: (a) the CAVs drive in a safer manner with respect to other surrounding vehicles and traffic signal control devices; (b) improve CAV decisions at the onset of a yellow indication and eliminate the probability of a vehicle being caught in the dilemma zone; and (c) reduce queue sizes and shockwave speeds formed upstream of traffic signals.

The team was carefully assembled to provide the needed expertise (breadth and depth) to conduct the proposed innovative ADS demonstration. Specifically, the team includes experts in traffic signal systems, vehicle systems engineering, communication, system integration and implementation, research, data storage and security, and vehicle testing. The project team will be led by the Center for Sustainable Mobility (CSM) at the Virginia Tech Transportation Institute (VTTI), with support from the VTTI Information Technology (IT) team, the Electronics Research Laboratory (ERL) of Volkswagen Group of America, Traffic Technology Services, Inc. (TTS), and the Virginia Department of Transportation (VDOT).

CSM has conducted research in a number of critical areas related to this effort. First, they developed models to capture driver stop/go behavior at the onset of a yellow indication. These models were then used to enhance the computation of yellow timings by considering the risk associated with being caught in the dilemma zone [5], vehicle characteristics (e.g., buses and trucks) [6, 7], weather effects [8-10], and driver aggressiveness [11]. CSM researchers have also developed and field-implemented safe and ecological driving strategies for CAVs approaching a traffic signalized intersection displaying a red indication [12]. Using Signal Phasing and Timing (SPaT) data and predictions of queues, the model estimates the optimum vehicle trajectory for a single signalized intersection [13-17]. The system was implemented in a level-2 CAV and field-tested on the Virginia Smart Roads test facilities [18, 19]. These models have recently been extended to predict the queue length and the queue discharge time while computing the optimum vehicle trajectory [20] and are currently being extended to consider multiple signalized intersections. Furthermore, CSM researchers recently developed and evaluated a Decentralized Nash Bargaining (DNB) traffic signal controller [21-24]. The DNB controller overcomes the major disadvantages of current, fixed-time, actuated, and adaptive traffic controllers, for which the controller must go through a fixed sequence of phases. This DNB controller has been tested on a number of networks within a simulation environment, including downtown Los Angeles (457 signalized intersections), producing significant improvements in network efficiency. Since the DNB controller is decentralized, it provides a robust and easily scalable system. Finally, CSM researchers are developing techniques to estimate the number of vehicles approaching a traffic signal using probe CAV and fixed-sensor data [25] for use in the DNB controller.

Recently, VDOT, Audi of America (a subsidiary of the Volkswagen Group of America), and TTS announced that more than 1,450 traffic signals in the Northern Virginia area are now sharing real-time data with Audi's Traffic Light Information (TLI) technologies, including Green Light

Optimized Speed Advisory (GLOSA) and “time-to-green.” The information sharing between VDOT and Audi has the potential to lead to improved operations and enhanced safety on arterial roadways. TLI informs drivers stopped at a red traffic signal when the traffic signal will change to green, and GLOSA provides speed recommendations to drivers to minimize stops at red traffic signals. Notably, the TTS V2I service is the largest single data provider in North America.

This project will build on the various CAV research and field implementation efforts conducted by the team members to develop and execute a unique demonstration of a fully integrated CAV and traffic signal control (CAV-TSC) system on real roadways.

Over the past decade, VTTI has conducted a number of naturalistic studies that involve the sharing of data. These projects include the National Highway Traffic Safety Administration-sponsored 100-Car Naturalistic Driving Study, which was the first large-scale naturalistic driving study ever undertaken. Since then, VTTI has led numerous naturalistic driving studies involving the collection of critical transportation information using VTTI-developed data acquisition systems (DASs). These DASs collect and store large amounts of continuous transportation data from the driving environment, including video, vehicle network information, and additional sensor information such as radar, Global Positioning System (GPS), and acceleration data. Leveraging VTTI’s extensive data collection experience, the team will collect and share the project data with USDOT and the public throughout the project duration. The team will share the project data in real time or at periodic batch updates depending on the data type. The team will also develop a data risk management plan to minimize data breach risks, including cybersecurity threats and vulnerabilities.

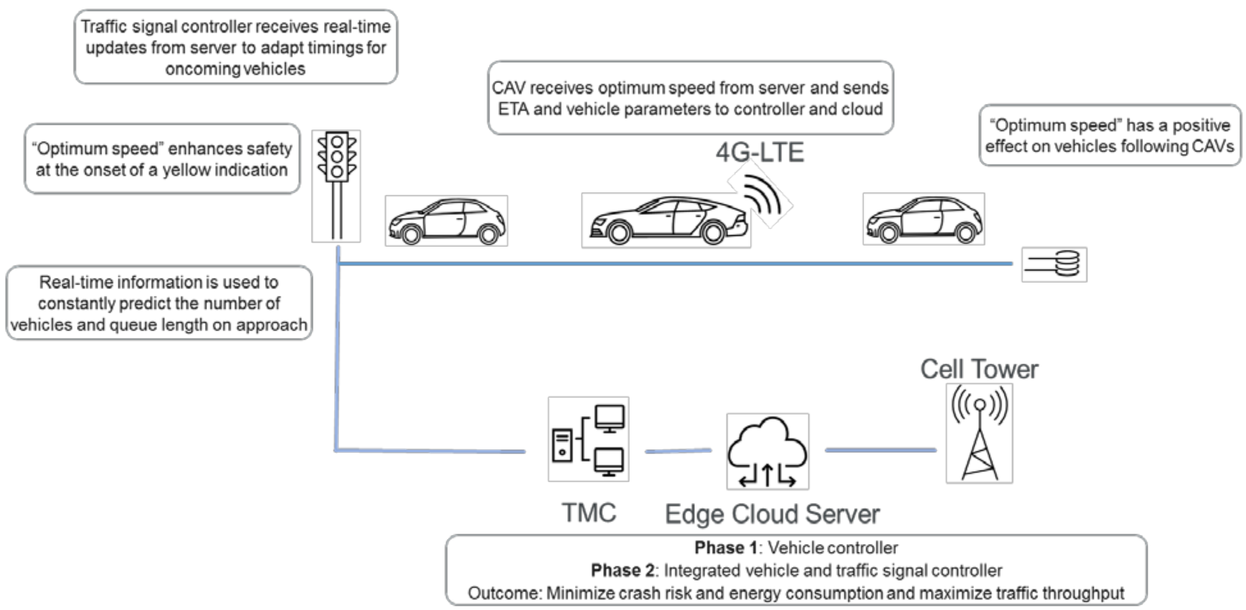


Figure 2: Proposed system architecture.

The team will conduct field tests using at least two L2+ or higher CAVs (supplied by Audi) along a signalized arterial in the Blacksburg/Christiansburg, VA area and an arterial in Northern Virginia. L2+ is somewhere between L2 and L3 control. Unlike L2 control, L2+ control allows vehicles to accelerate from a complete stop without any driver input. Unlike L3, in L2+ control the driver does not shift "safety-critical functions" to the vehicle and still has to be alert at all times. Given that we are currently not aware of the exact timeframe for releasing L3 ADSs, we are committing to L2+ and would use L3 CAVs if available in the final field demonstration. The test vehicles will receive real-time traffic SPaT data from VDOT-operated traffic signals using TLI technologies through the 4G-LTE cellular network, as illustrated in Figure 2. Vehicle control computations will be performed either on the cloud and sent as speed recommendations to vehicles and/or locally on the vehicles. Traffic signal computations will also be carried out on the cloud and sent as recommendations to the traffic signal controllers. Both vehicle and traffic signal control strategies will be integrated to ensure a fully integrated vehicle and traffic signal control system, referred to as CAV-TSC. The following actions will be taken to guarantee public safety: (a) VDOT will ensure all federal, state, and local laws, rules, and regulations are followed and will oversee and assist with the field tests in collaboration with the various team members; and (b) ERL will train test drivers, who will be present in all CAVs, to ensure they have sufficient knowledge of when and how to take control of the vehicle in the event that driver intervention is needed.

The project is divided into three phases that will be executed over a period of four years. The first phase involves preliminary testing of vehicle control algorithms at a controlled ERL facility in Belmont, CA. This phase will be completed in the first six months of the project. The second phase involves the control of CAVs in response to surrounding system dynamics. A demonstration of the CAV system using L2+ CAVs will be conducted in the Blacksburg, VA area at 24 months after the start of the project. The third phase involves the simultaneous optimization of the traffic signal timings and vehicle trajectories (known as the CAV-TSC system) of potentially L3 CAVs. Field testing of the CAV-TSC system will be conducted in the Blacksburg, VA area followed by a final demonstration in both Blacksburg and Northern Virginia at 40 months after the start of the project.

Goals

The proposed project will develop and demonstrate an advanced ADS that is fully integrated with traffic signal control (CAV-TSC) along signalized arterials with a primary focus on safety. The proposed innovative CAV-TSC system has the potential to save lives by drastically reducing human error and optimizing vehicle trajectories to smooth traffic operations. The system will also improve the efficiency of the transportation system by increasing throughput through signalized intersections and reduce energy consumption by optimizing and smoothing vehicle trajectories. The system will produce safety benefits by: (a) allowing CAVs to drive in a safer manner with respect to other surrounding vehicles; (b) improving CAV decisions at the onset of a yellow indication and eliminating the probability of a vehicle being caught in a dilemma zone; and (c) reducing queue sizes and shockwave speeds formed upstream of traffic signals. In developing and demonstrating the proposed CAV system, VTTI is partnering with an automaker (ERL of Volkswagen Group of America), a traffic engineering firm specializing in traffic signal control (TTS), and a state department of transportation (VDOT).

CAVs (an ADS application) can significantly reduce driver Perception-Reaction Times (PRTs) from the typical range of 0.7–3 s to 0.5 s. Since CAVs can calculate the exact stopping distance using vehicle speed and location data together with SPaT data received from traffic signal controllers, the driver decision zone (also known as the option zone) can be eliminated. In addition, by controlling the traffic signal timings, the driver dilemma zone can be eliminated by extending the green time for vehicles caught in the dilemma zone. As part of the proposed demonstration, the team will evaluate the interactions of CAVs with non-CAVs along signalized arterials. In particular, we will evaluate all conflict points at signalized intersections. A typical four-legged signalized intersection has eight merge and eight diverge conflict points along with 16 crossing conflict points. Rear-end and sideswipe collisions may occur at merge/diverge conflict points. In addition, 12 crossing movements are associated with left-turning vehicles, which can crash into passing through vehicles. The team will carefully evaluate the possible safety conflicts during the field tests based on video recordings of sample intersections. Furthermore, rear-end crashes are common occurrences when vehicles encounter shockwaves. The proposed demonstration will show the ability of CAV control to reduce shockwave propagation speeds along with stop-and-go waves, resulting in improved safety and reduced fuel consumption.

The proposed work will build on the various CAV research and field implementation efforts of the team members to develop and execute a unique field ADS demonstration of a fully integrated CAV and traffic signal control system, entitled the CAV-TSC system. The team will conduct field tests using at least three L2 or higher Audi vehicles along a signalized arterial in the Blacksburg/Christiansburg, VA area and along an arterial roadway in Northern Virginia. The exchange of data will be performed using a 4G LTE communication protocol at both test sites. Testing will include the following activities:

1. Test the safe integration of the proposed traffic signal system and test vehicles (L2+ Audi vehicles) with VDOT traffic signals. If available from Audi, L3 vehicles will be used in the final demonstration.
2. Review system safety, Operational Design Domain (ODD), Object and Event Detection and Response (OEDR), Fallback (Minimal Risk Condition), Vehicle Cybersecurity, Occupant Protection, and compatibility of the test vehicle for the proposed field demonstrations.
3. Test the system on a controlled test facility before field testing on public roads. VTTI's Smart Roads and ERL's testing facilities will be used for these purposes.

Data collected from the ADS demonstration will be shared though VTTI's database server and the Secure Data Commons (SDC), which is operated by the USDOT. All ADS demonstration data will be shared in real time or through periodic batch updates so that researchers and public shareholders can access and analyze project data.

Focus Areas

The proposed project aligns with the USDOT focus areas as follows:

a. **Significant Public Benefits**: The objective of this project is to develop and demonstrate a CAV application that simultaneously improves traffic safety, reduces traffic congestion, and increases energy efficiency. The innovative system will significantly reduce human error-related crashes along signalized arterials as well as improve transportation system efficiency through the proposed CAV-TSC system. In particular, the proposed platoon control and vehicle discharging system will increase the saturation flow rate of roads and reduce lost time at signalized intersections, thereby increasing the vehicular throughput of the transportation system. The transportation sector is the major consumer of energy in the U.S., where it accounts for two thirds of fuel consumption. Given that energy independence is highly linked to U.S. energy security, the project provides public security benefits by reducing energy imports. We expect that the proposed optimum vehicle trajectory and traffic signal control (CAV-TSC system) will improve the energy efficiency by approximately 10%–20% based on findings of previous studies [26, 27].

b. **Addressing Market Failure and Other Compelling Public Needs**: A number of vehicle manufacturers, technology companies, and research institutes (e.g., Mercedes-Benz, General Motors, Nissan, Tesla, Waymo, and Nvidia) have developed and tested prototype ADS-equipped vehicles. For instance, as of 2018, Waymo has driven their test vehicles more than 5 million miles in 6 U.S. states and in more than 25 cities. Furthermore, many companies have tested ADS-equipped vehicles in different environmental conditions, including extreme temperatures and wet weather. However, few companies have tested ADSs along signalized arterials. This project will be the first to demonstrate and quantify the effects of an advanced traffic control system using multiple CAVs on public roads. The demonstration of CAV technology at multiple signalized intersections is risky and complex for any single private sector entity. Thus, support from local governments is needed. Accordingly, the assembled team includes the key partners needed to achieve the desired objectives.

c. **Economic Vitality**: The successful implementation of the proposed project will support economic vitality at the national and regional level by reducing traffic congestion and energy consumption. A recent INRIX study quantified the total cost of traffic congestion on U.S. drivers as $305 billion in 2017, including direct costs such as fuel and time along with indirect costs such as increased costs due to delays [28]. The proposed system is expected to significantly reduce traffic delay at intersections, reduce major traffic bottlenecks, reduce vehicle fuel consumption, and support the economic strength of the U.S.

d. **Complexity of Technology**: The team will perform the demonstration using multiple Audi vehicles equipped with at least L2+ ADSs. The proposed CAV-TSC system involves the integrated control of CAVs and traffic signal timings to achieve the desired benefits. During the demonstration on public roads, the test vehicles will integrate inputs from V2I and V2V communication by interfacing with the vehicle bus systems. The test vehicles will be equipped with networked computers along with Flexray, LIN, and CAN reading equipment. The vehicles will decode the signals and communicate them via in-vehicle WiFi through a cloud server. The proposed system is complex because it combines CAV and traffic signal control to develop a fully integrated CAV-TSC system.

e. **Diversity of Project**: The proposed CAV-TSC system will support a variety of communities, including those in urban, suburban, and rural environments, by improving traffic safety and reducing traffic congestion, energy consumption, and emissions. The proposed system can also be implemented in a variety of transportation modes, including freight, personal mobility, and buses.

f. **Transportation-challenged Populations**: The demonstration will be conducted using Audi CAVs equipped with all the hardware required for at least L2+ driving (potentially L3 driving). These CAVs will be able to manage most aspects of driving, including monitoring the environment, braking and stopping, accelerating from a complete stop, and lateral vehicle control. The proposed advanced CAV-TSC system will significantly improve the safety at and near signalized intersections by eliminating decision and dilemma zones and smoothing traffic operations to support transportation-challenged populations, including older adults and individuals with disabilities, who typically have longer PRTs and are thus more prone to be involved in crashes.

g. **Prototypes**: The team will develop a prototype CAV-TSC system that will be tested in the field. The planned demonstrations will meet all applicable safety standards.

Requirements

The proposed effort satisfies all requirements contained in the NOFO as follows:

1. The demonstration focuses on the research and development of automation and ADS technology. We guarantee that our demonstration will involve at least L2+ ADS-equipped vehicles, and we hope to conduct the final demonstration with L3 ADS-equipped vehicles, if the vehicles are available at that time.
2. The project involves two physical demonstrations, one with L2+ ADS-equipped vehicles and one with potentially L3 ADS-equipped vehicles. If L3 CAVs are not available for the final demonstration, the team will use L2+ CAVs that perform full longitudinal and lateral control of vehicles including braking, accelerating from a complete stop, and lateral lane control.
3. The demonstration will include the gathering and sharing of data with the USDOT throughout the project in near-real time. The data will be accessible to both USDOT and the public.

Approach

This section describes the technical approach to implement and evaluate the demonstration, including system development and the evaluation of the demonstration field-testing results. Briefly, the system will first involve CAV control (phase 2). The system will then be extended by integrating the traffic signal control with the vehicle control to develop the fully-integrated CAV-TSC system. This system will be a bi-level controller, with the traffic signal controller operating at the upper level, and the CAV controller running at the lower level. Feedback between the two controllers will allow each controller to benefit from the other. For example, the traffic signal controller will use the CAV controller to predict vehicle arrivals more accurately and thus optimize the traffic signals using better data. Alternatively, the traffic signal controller will share its control strategy with the CAVs to improve the control strategies by accounting for future changes in the traffic signal timings.

System Algorithm Development

Green Indication Vehicle Control

The control of CAVs approaching a traffic signal displaying a green indication involves the consideration of three scenarios: (1) the initial discharge from a queue, known as the start loss; (2) queue discharge at the saturation flow rate for vehicles queued during the red indication; and (3) vehicle arrival after the queue is discharged until the end of the green indication. This section addresses scenarios 1 and 3; scenario 2 is discussed later when describing the control of vehicles arriving during a red signal indication because the logic is identical to that used for vehicles approaching a standing queue.

To address scenarios 1 and 3, two control algorithms will be developed as part of this project: (1) a controller to reduce start loss by sharing SPaT information; and (2) a controller to platoon CAV arrivals after the discharge of the queue to maximize throughput through multiple signalized intersections. These two control algorithms are described briefly in this section.

Controller to reduce start loss by sharing SPaT information: Empirical observations have shown that the discharge headways for the first few vehicles in a standing queue at a traffic signal are typically longer than the steady-state saturation flow headway, as illustrated in Figure 3. The Highway Capacity Manual (HCM) describes this phenomenon as start loss [29]. The start loss is attributed to driver PRTs to the switch in traffic signal indication from red to green along with delays associated with vehicle acceleration. Consequently, start loss can be reduced by communicating SPaT information to CAVs to allow them to discharge as soon as a traffic signal turns green. The team proposes developing a coordinated start platoon to allow vehicles to start accelerating simultaneously once the traffic signal turns green. The proposed operation is expected to significantly increase the throughput at congested intersections.

Controller to platoon CAV arrivals after the discharge of the queue to maximize throughput: The team will develop a vehicle platoon strategy that maximizes green interval utilization. Platooning employs wireless vehicle communication and various control algorithms to enhance vehicle-following capabilities and thus increase roadway capacity. The operational concept of platooning represents an evolutionary advancement over conventional cruise control and adaptive cruise control systems by utilizing V2V communication to automatically synchronize the movements of multiple vehicles within a platoon. Project lead CSM is currently developing vehicle platooning control strategies as part of a U.S. Department of Energy (DOE) project. As part of the DOE effort, CSM has already (a) designed a platooning algorithm for freeways; (b) validated the performance of the platooning controller for a multi-vehicle platoon; (c) developed and tested a new simple and efficient platooning algorithm designed to handle any arbitrary number of platooned vehicles; and (d) developed models to relate the drag coefficient to the vehicle position and spacing within a platoon for car, bus, and truck platoons. As part of the proposed project, we will expand on this DOE work to extend the platoon controller to signalized arterials. The proposed platoon system will utilize SPaT information from the infrastructure to improve the traffic stream mobility along signalized arterials. The system will inform a platoon of the most efficient trajectory to proceed through multiple closely spaced signalized intersections. By tightly coordinating in-platoon

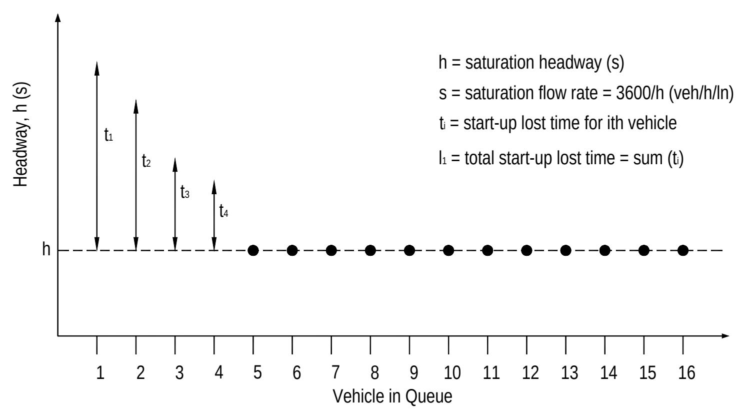


Figure 3: Concept of start loss at a traffic signal.

vehicle movements, the gap between vehicles will be reduced, resulting in greater roadway throughput, smoother traffic flow, and improved traffic flow stability. After a vehicle leaves the platoon, the remaining platooned vehicles will maintain the headway and acceleration parameters based on the optimized operations derived for the platoon. The development of this controller will include the creation of a detailed operational and safety review plan for each operational scenario.

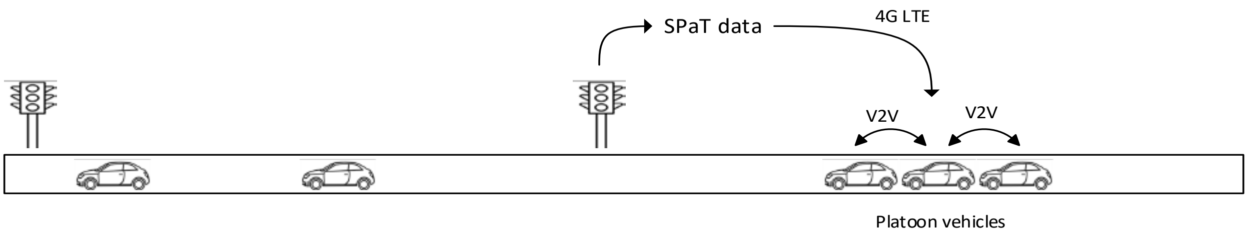


Figure 4: CAV platooning.

Yellow Indication Vehicle Control

The stopping distance, which is a function of vehicle speed, the driver's PRT, and the acceptable deceleration rate, is defined as the distance required for a vehicle to come to a complete stop upstream of the intersection stop bar (d_s, in m) and is computed as

$$d_s = vt + \frac{v^2}{2g(f_b \eta_b \mu \pm G)}, \quad (1)$$

where v is the speed of the approaching vehicle (m/s), t is the driver PRT (s), g is the gravitational acceleration (9.81 m/s^2), f_b is the driver brake pedal input [0,1], η_b is the braking efficiency [0,1], μ is the coefficient of roadway adhesion (unitless), and G is the roadway grade (decimal).

The running distance d_r is computed as

$$d_r = vy, \quad (2)$$

where y is the yellow time (s). The yellow time is then computed by equating Equations (1) and (2) and solving for y. The typical values for t and f_b used in Equation (1) for the design of yellow timings are 1 s and 0.33 (resulting in a deceleration level of 3 m/s^2), respectively.

The driver's approach speed and distance from a signalized intersection at the onset of a yellow indication affects the driver's decision to stop or proceed. Drivers can either come to a safe stop if they are sufficiently far from the intersection or clear the intersection during the yellow interval if they are sufficiently close. The inability to perform either option successfully is attributed to a shortcoming in the design of the signal timings and is termed the design dilemma zone in some literature [30]. This dilemma zone is created when the minimum stopping distance is greater than the maximum running (clearing) distance (d_r). Figure 5 illustrates the option and dilemma zones. When a vehicle approaches an intersection during a yellow interval, if $d_s < d_r$, and the vehicle is farther than d_s or closer than d_r ($d_s < d < d_r$), the driver is in an option zone and can choose to either stop or proceed without running a red light. If $d_s > d_r$, and the vehicle is placed between them such that $d_r < d < d_s$, the vehicle is in a design dilemma zone and can neither stop nor clear the intersection. We have demonstrated that even if the yellow timings are correctly designed, a driver can still be caught in a dilemma zone [5]. This can be a result of the driver having a longer PRT than the design value of 1 s (e.g. older or distracted drivers), the driver having to decelerate at a less aggressive level (e.g. wet pavement, truck, or bus), and/or the driver traveling at a speed higher than the design speed.

A controlled field study conducted by CSM researchers generated stop/run probabilities versus the time to intersection (TTI) at the onset of the yellow signal indication, as illustrated in

Figure 6. The figure demonstrates that the further the driver is from the intersection (larger TTI), at the onset of yellow the more likely they are to stop. The 0.9/0.1 probability of stopping/running was 3.9 s from the stop line at the onset of yellow, while the 50% stop/run decision point occurred when the yellow indication was triggered when the vehicle was 3.0 s from the stop line. The figure clearly demonstrates the variability in driver decision-making along with the errors drivers make when executing these split-second decisions. CAVs provide a unique opportunity to eliminate driver errors associated with the decision to stop or proceed at a yellow signal. Specifically, by tracking CAV location via GPS and receiving SPaT information from the traffic signal controller, a CAV can be controlled to execute the correct decision in a fashion that minimizes shockwaves within the traffic stream. This would result in safer driving at and near intersections.

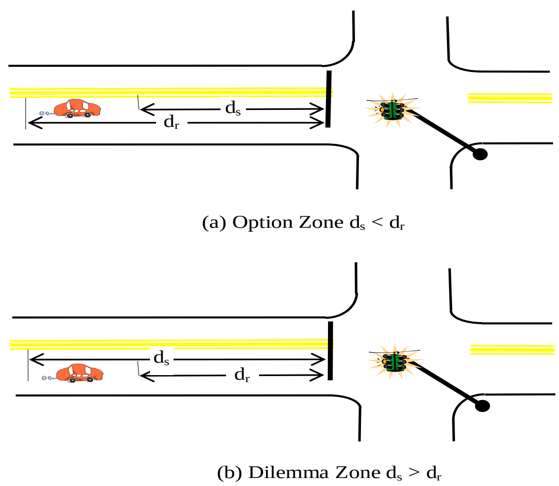


Figure 5: Schematics showing option (a) and dilemma (b) zones

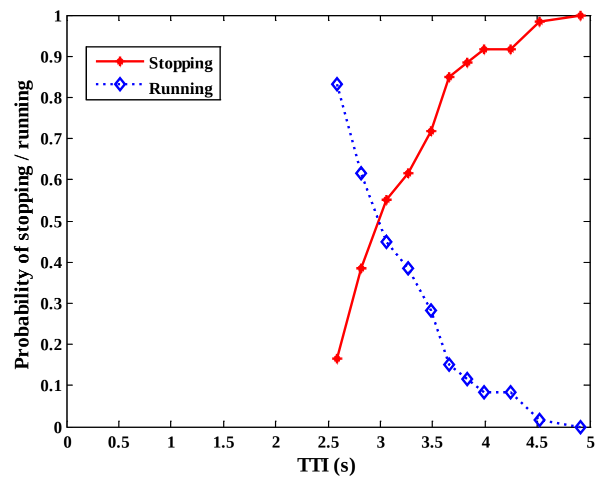
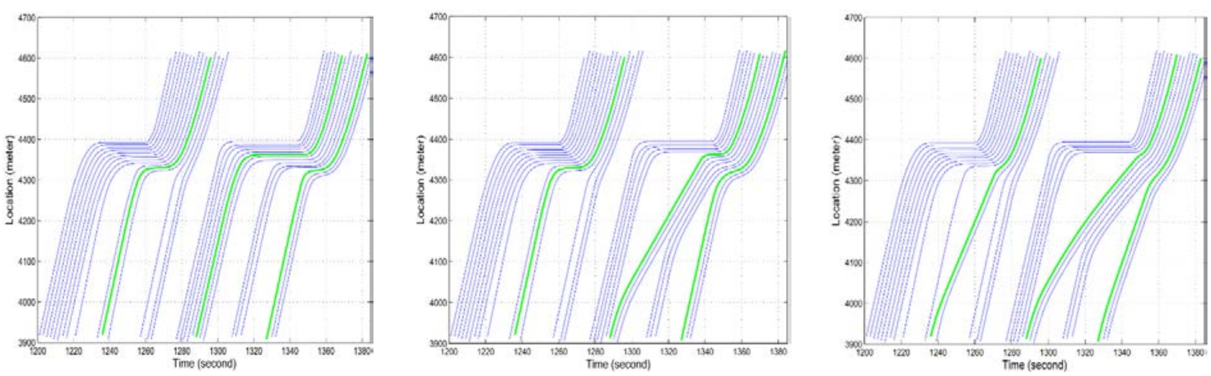


Figure 6: Probability of stopping/running as a function of TTI

Given that communication and mechanical latencies sum up to approximately 0.5 s, which is shorter than typical driver PRT (between 0.7 and 3 s and assumed to be 1 s in the design of yellow signal times), the system should be able to respond quicker and more precisely than human drivers since the vehicle sensors will provide more reliable and timely data to compute the optimal decision. For example, considering an approach speed of 35 mi/h (15.56 m/s), a latency of 0.5 s, a brake pedal input of 0.33, a braking efficiency of 1.0, and a coefficient of friction of 1.0, the stopping distance would be 45.15 m, which is equivalent to a TTI of 2.9s. Thus, the proposed system would make the vehicle stop if it were 45.15m (2.9s) or further away from the intersection stop bar at the onset of yellow. For shorter distances, the vehicle would proceed to prevent aggressive deceleration maneuvers that could result in rear-end crashes. Notably, vehicle sensors can also compute the roadway coefficient of friction, which is affected by factors such as pavement wetness, and use that information to compute the optimum decision while accounting for the roadway surface condition. As part of this project, the team will develop a system that decides and executes the optimum stop/go decision at the onset of a yellow indication considering all the factors discussed earlier.

Red Indication Vehicle Control

A previously developed safe and ecological vehicle controller [13-17] will be integrated with the CAV to optimize its trajectory as it approaches a traffic signal that is either displaying a red indication or is discharging a queue. The safe and ecological driving system was developed to (1) assist vehicles in driving smoothly while traversing signalized intersections using data acquired from V2I and V2V communications, and (2) improve traffic safety by reducing stop-and-go traffic waves, thereby reducing rear-end crashes. To ensure a smooth trajectory, the trajectory is generated to minimize vehicle energy consumption, given that energy consumption is highly sensitive to the combination of vehicle acceleration and speed (also known as speed volatility). The system was implemented in a L2 CAV and field tested on the Smart Roads test facility [18, 19]. The model was recently extended to predict the queue length and the queue discharge time while computing the optimum vehicle trajectory [20] and is currently being extended to consider multiple signalized intersections in constructing the optimum trajectory. The algorithm was incorporated in the INTEGRATION software, a state-of-the-art microscopic traffic simulation software capable of evaluating the system-wide impacts of CAV applications [31]. The team has already tested the algorithm within a traffic simulation environment and in the field [32-34]. The queue prediction algorithm [35, 36] ensures that vehicles approaching queues (highlighted in green in Figure 7) proceed smoothly through the intersection without having to come to a full stop, as shown in Figure 7(c). Note that these vehicles incur long full stops for typical human driving, while they have short full stops in the case of safe and ecological driving without queue prediction. Based on the simulation results, these smoother trajectories resulted in reductions in internal combustion engine vehicle fuel consumption levels by up to 40%.

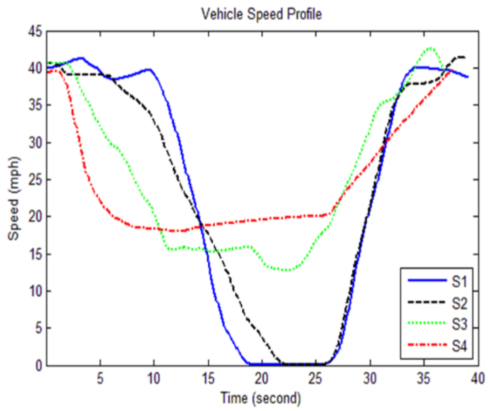


(a) (b) (c)

Figure 7: Vehicle trajectories around a single-lane signalized intersection: (a) basic case; (b) safe and ecological drive without considering queue impacts; and (c) safe and ecological drive considering queue impacts

The controller was also implemented in a CAV and tested by 30 participants on the Virginia Smart Road in Blacksburg, VA [37, 38]. Compared to an uninformed driver, the longitudinal control using the proposed controller (S4) helped vehicles traverse the intersection more smoothly, resulting in fuel and travel-time savings of 37.8% and 9.3%, respectively (Figure 8).

Further enhancements will allow the system to deal with adaptive and/or traffic-responsive signal control systems and expedite the computations so that they can be completed in approximately one second. This will ensure that the vehicles use the latest information while generating the optimum trajectories.



(a)

Direction	Red phase offset (second)	Difference between S2 and S1 (%)	Difference between S3 and S1 (%)	Difference between S4 and S1 (%)
Downhill	10	-39.8	-39.4	-42.8
	15	-32.6	-45.0	-53.2
	20	-0.7	-23.9	-43.6
	25	-4.4	-17.5	-39.8
Uphill	10	-28.5	-31.7	-30.5
	15	-18.5	-23.9	-40.9
	20	-10.9	-21.5	-26.7
	25	-10.5	-18.7	-25.0
Average		-18.3	-27.7	-37.8

(b)

Figure 8: Results of field testing the proposed controller: (a) sample vehicle speed profiles from 250 m upstream of the traffic signal stop bar to 180 m downstream and (b) fuel consumption. Testing considered four scenarios: S1 = uninformed driver; S2 = a driver provided with a red indication countdown; S3 = a driver following an auditory recommended speed (manual controller); and S4 = a vehicle with controlled longitudinal motion (automated controller)

Prediction of Traffic Signal Timings

Traffic signal controllers focus on immediate requests from vehicles in the vicinity of the intersection through detection or recurring parameters. By design, the controller will only understand the immediate switch points within the next 10 to 20 s; beyond this point in time, the controller does not have confidence regarding the next switch points. Additional hardware and software architectures are needed to support the data requirements and computation for longer-term predictions. To maximize the potential of CAV applications, additional levels of prediction are required.

TTS has developed a patented technology (USPTO #US9396657B) that emulates both the traffic signal control logic and the control parameters, as reflected by controller firmware and timing plan data, respectively. When input with the same detection, the emulator program will react exactly as the field controller and generate the signal output, including signal group state changes. The traffic pattern is simplified into signal phase calls (vehicle phase, public transit, pedestrian push buttons, or bicycle-specific phases). By combining long-term calls, immediate past call history, and current call status, the probability of phase call activation or extension is forecast for the next few cycles (prediction horizon). This forecast call spectrum is coupled with the emulator program to fast-

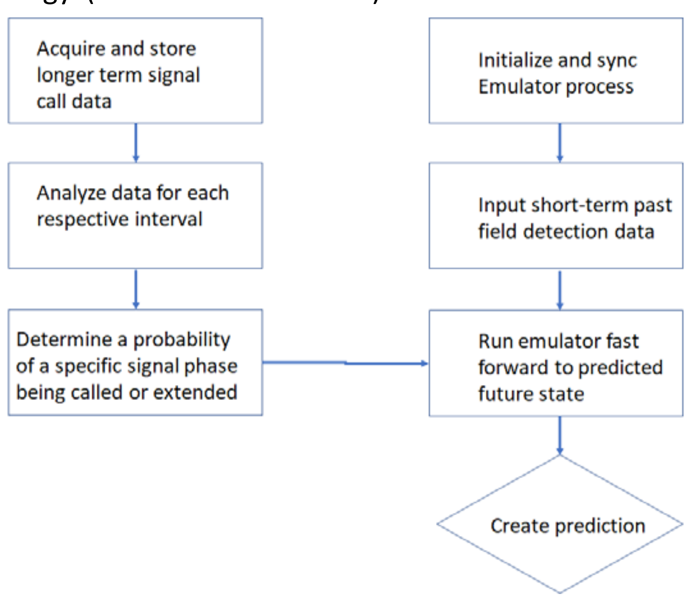


Figure 9: Emulation-based signal state change prediction workflow

forward to the end of the prediction horizon. The generated signal output then becomes the predicted signal state changes. This method was validated in the field in multiple countries and provides the most important data element in the SPaT message.

To support in-vehicle applications such as Audi connect® Traffic Light Information services, the SPaT message must be expanded to include other necessary information using additional supporting algorithms and modules. The key SPaT data elements include: (1) signal group ID, (2) timestamp of prediction; (3) current signal status (e.g., protected red/green or permissive green/flashing yellow arrow; (4) predicted signal switch times; (5) quality of prediction (confidence levels); (6) min/max time to switch times; (7) emergency vehicle preemption/public transit priority; and (7) status/failure mode. The SPaT message is delivered every second; when the vehicle is matched to specific signalized intersections, only the SPaT for that signal is queried and delivered to the onboard computer. As part of this project, the algorithm will be enhanced and included in the queue and multi-signal prediction algorithms described earlier.

CAV-based Actuated Control

Audi Electronics Ventures ERL and TTS have jointly developed the "Virtual loop," an algorithm that issues a "call" to a traffic signal controller via National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) when a vehicle is approaching. The vehicle is in constant contact with the algorithm and provides distance, speed, and time to destination when approaching a traffic signal. The vehicle detects that it is approaching a traffic signal by receiving a "SAE J2735" map-topology message and matching to it. Additionally, the vehicle may also receive SPaT messages. The communication between the vehicle and the server algorithm occurs via NTCIP. The server communicates via a virtual private network to the traffic signal controller. This system has been successfully tested by Audi/ERL/TTS in Las Vegas with the support of the Freeway and Arterial System of Transportation (Nevada Department of Transportation). The total delay of the approaching connected vehicle was significantly reduced under low-traffic-volume scenarios. When the vehicle crosses the limit line or diverts from the Map-Topology, a cancel message is sent to cancel any remaining calls. The "call" message acts like a real loop detector and therefore gives the connected vehicle fair priority. The virtual loop has many safety and energy-saving advantages related to the advanced detector. We believe that this represents the next step in improving V2I communication without the burden of infrastructure investments, since this system can be realized through existing cellular communication channels that Audi/TTS and DOTs have created for traffic signal information networks.

Virtual detectors have additional safety benefits by dynamically eliminating the dilemma zone. The dilemma zone, as was described earlier, arises when the target moving vehicle is unable to either safely stop or clear the intersection at the onset of yellow. Fixed-location advanced dilemma zone detection systems have been investigated; however, existing systems fail to solve the problem at scale when considering nationwide deployment. The virtual loop may potentially solve this problem. Based on initial work completed by ERL and TTS, the following research and development will be necessary:

- **Design the CAV-based actuated control logic**. As a novel approach, the CAV-based actuated control logic must be demonstrated in the current signal control framework, which balances safety, user fairness, and other fail-safe considerations. For example, any phase call must be served within the same cycle to avoid the incorrect perception of malfunctioning signals, possibly leading to red indication violations. At the same time, the control logic must anticipate the right-of-way requests from conflicting traffic flows.

- **Develop the overall system for feasibility and scalability**. Any engineering design must pass the feasibility and scalability test for potential implementation in the physical world. This CAV-based actuation control system is no exception; it must co-exist with current control systems and utilize state-of-the-practice infrastructure, including communications, controllers, and cloud backends. For example, will a request from an equipped CAV cause any harm to current signal operations? Will the system degrade at the cost of the benefits of CAVs? Once proven successful, what is are possible paths toward wider deployment? These research questions will be of interest to the public-sector organizations that will oversee policy formulation in the near future regarding infrastructure development for CAVs.

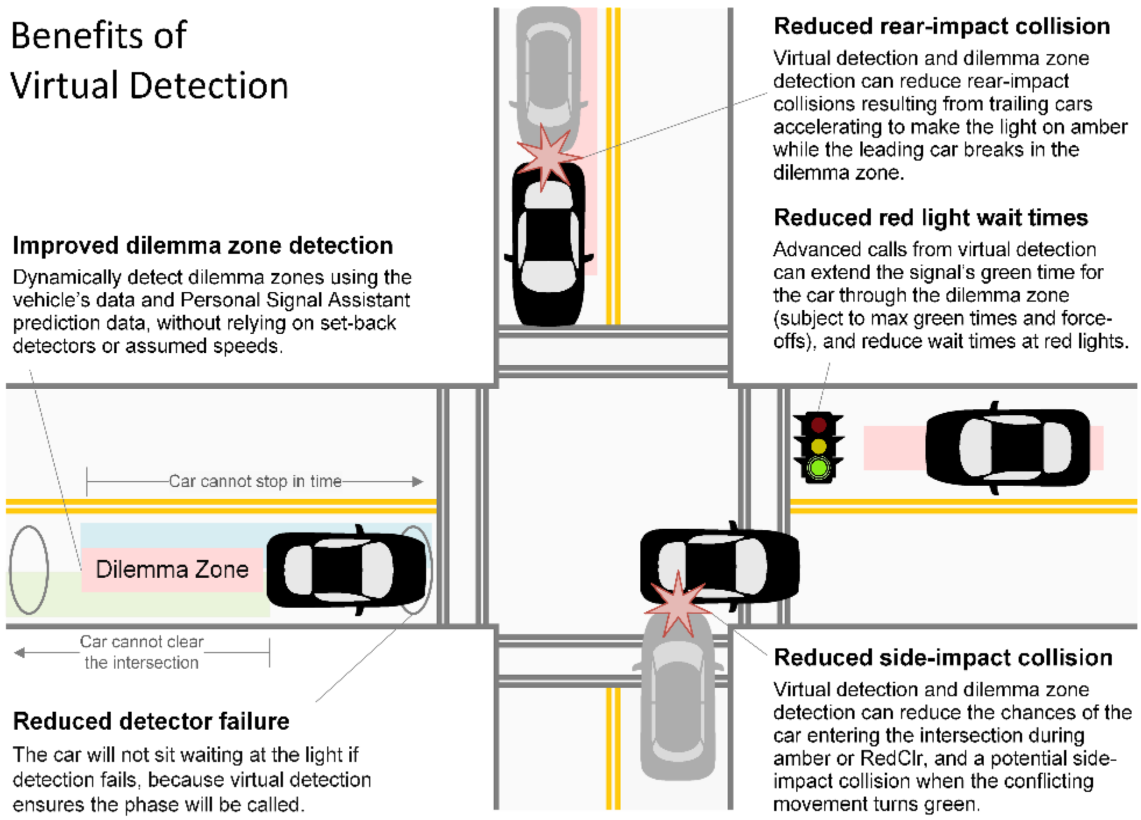


Figure 10: The virtual loop reduces the chances of rear-end and side-impact collisions by providing dynamic dilemma zone detection

Decentralized Nash Bargaining (DNB) Traffic Signal Control

Current traffic signal control systems can be categorized into the following categories: fixed-time control (FP), actuated control (ACT; this includes fully actuated and semi-actuated control), traffic responsive control, and adaptive control. One of the main disadvantages of traditional traffic control systems is that they operate within a pre-defined phasing scheme. In actuated controllers, the controller may skip a specific phase if traffic conditions warrant skipping that phase; however, the controller still proceeds to the next phase in the pre-defined phasing plan/scheme. In addition, current sophisticated traffic control systems use hierarchies that either partially or completely centralize the decisions, making the systems more vulnerable to failures in one of the master controllers. Decentralized systems offer several advantages over centralized control systems, namely: (1) they are computationally less demanding as they only require information from surrounding intersections/controllers; (2) they are scalable and easy to expand by inserting new controllers into the system; and (3) they are robust and inexpensive to operate as there is no need for a reliable and direct communication network between a central computer and the local controllers in the field.

Game theory is adaptable to traffic fluctuations and the randomness of traffic systems. Consequently, game theory has the potential to alleviate traffic congestion more effectively than the more commonly used FP and ACT systems. The research team recently developed a novel traffic control system using the Nash Bargaining (NB)-theoretic algorithm. In this algorithm, a bargaining situation is defined as a situation in which multiple players with specific objectives cooperate and benefit by reaching a mutually agreeable outcome (agreement). Bargaining theory involves two concepts: the bargaining process and the bargaining outcome. The bargaining process is the procedure that bargainers follow to reach an agreement (outcome), and the bargaining outcome is the result of the bargaining process. Nash adopted an axiomatic approach that abstracts the bargaining process and considers only the bargaining outcome. Bargaining theory is related to cooperative games through the concept of NB. The bargaining problem consists of three basic elements: players, strategies, and utilities (rewards). Bargaining between two players is illustrated in the two-player matrix shown in Figure 11. Each of the two players (P_1 and P_2) has a set of possible actions A_1 and A_2, and the outcome preferences are given by the utility functions *u* and *v*, respectively, as the players take relevant actions. The utility area (*S*) of the two-player cooperation game is shown in Figure 12; the vertices of the area are the utilities where each player chooses their pure strategy. The disagreement or threat point $d = (d_1, d_2)$ corresponds to the minimum utilities that the players want to achieve. The disagreement point is a benchmark, and its selection affects the bargaining solution. Each player attempts to choose their disagreement point to maximize their bargaining position. The DNB solution is obtained from a maximization problem where the solution (u^*, v^*) can be calculated as the point in the bargaining set that maximizes the product of the players' utility gains relative to their fixed disagreement point, as shown in Figure 12. The team has developed a NB-theoretic algorithm that optimizes traffic signal timings using a flexible phase scheme and applied this algorithm to isolated intersections, an arterial roadway, and medium- and large-scale networks. The system produced promising results with delay reductions of over 30% for an arterial network (six signalized intersections) and downtown Blacksburg (38 signalized intersections). The disagreement points were set to coincide with the maximum queue length that each player is willing to accept.

As part of the proposed effort, the NB-theoretic algorithm will be extended by: (1) integrating the DNB controller with commercial controllers; and (2) integrating the vehicle and DNB controllers to provide a unique integrated vehicle and traffic signal controller. The first extension can be achieved by running the real controller (FSC) freely and controlling it via NTCIP calls, holds, and force-offs. In this way, we can completely control the timing, but all safety-relevant functions will still be handled by the FSC. The second extension will involve a bi-level controller in which the traffic signal controller operates at the upper level, and the vehicle controller operates at the lower level.

		P2: A1	P2: A2
P1	A1	u_1, v_1	u_2, v_2
	A2	u_3, v_3	u_4, v_4

Figure 11: Two-player game matrix where P1 and P2 are the players, A1 and A2 are their actions, respectively

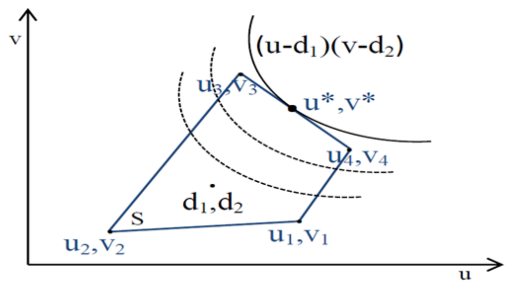


Figure 12: Feasible utility region for the two-player game together with the objective function contours

System Implementation

Vehicle Interface Installation

The vehicles used in the demonstration and field testing will be a combination of new Audi A6 (Generation C8; Figure 13) and other Audi vehicles. The vehicles will be equipped with all the hardware required for advanced driver assistance features. We will be able to carry out experiments with Traffic Jam Assist, an L2 functionality that automatically maintains a following headway and lane. With software modifications, it will be possible to carry out experiments using L2+ control, such as stopping at a traffic signals and accelerating from stops without driver input. Audi is a leading developer of L3 technology and strives to be the first OEM to release a L3 system to the market, as has been mentioned in the press. We anticipate that L3 vehicles will be available later in the project. In the event that L3 vehicles are not available, the team will use modified L2+ systems that allow for deceleration and acceleration from a complete stop.

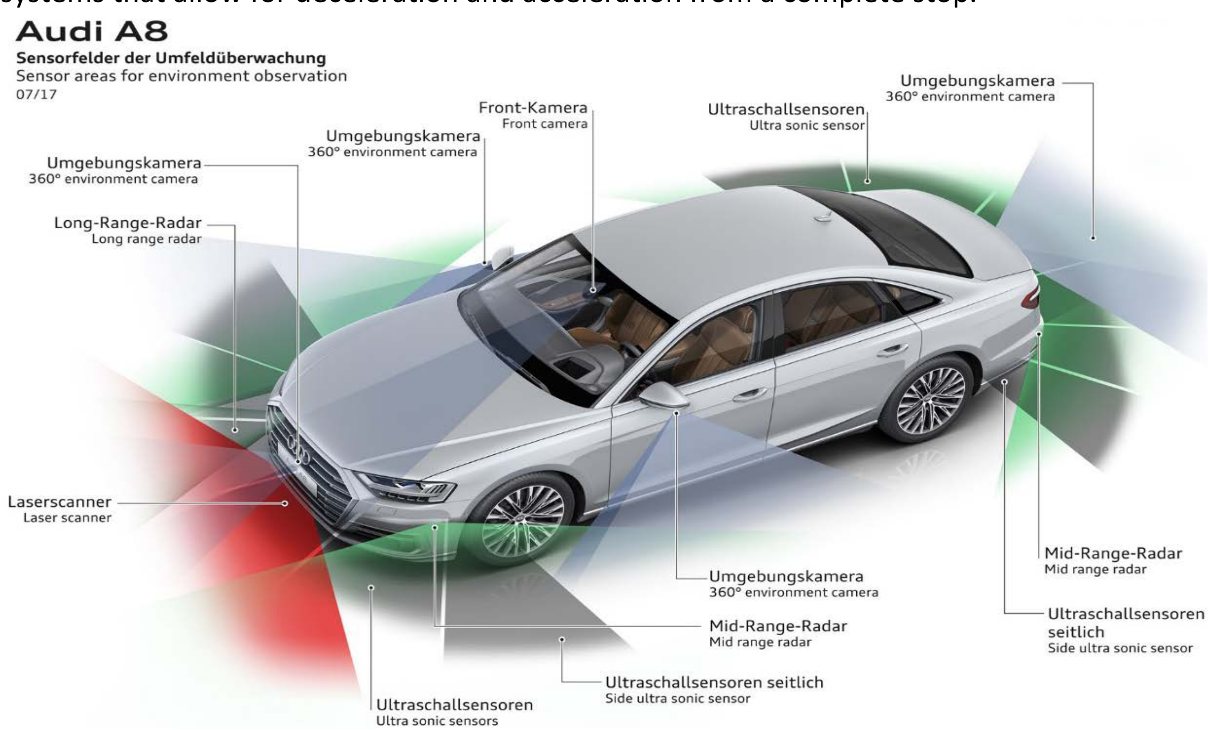


Figure 13: Vehicle features of the Audi A6, A7, and A8

While the Traffic Jam Assist-equipped vehicle has the ability to maintain the required distance to a vehicle in front, we propose to set the desired speed (input to the piloted system) from the centralized online server system that regulates the traffic flow. This is achieved by interfacing the vehicle bus systems. The desired Adaptive Cruise Control (ACC) input is set in the loop between the buttons and the vehicle systems. Audi has experience in integrating vehicle functions, such as ACC with the traffic signal system. This was first demonstrated in the Audi project “Travolution” from 2006–2010 [2].

The vehicle’s built-in cellular connection handles the vehicle online services, such as traffic signal information (Figure 14) and a WiFi Hotspot. Two-way communication is established between the server and the vehicle via cellular (4G LTE), as illustrated earlier in Figure 2.

Figure 14: Traffic signal information, on the market since 2016, now also includes GLOSA

Traffic Signal Controller Update

Team member TTS will use the existing open standard NTCIP protocol to communicate with the traffic signal controllers for control decision updates. TTS staff have developed a local adaptive control algorithm called Program for Local Adaptive Timing Optimization (PLATO) to provide second-by-second cycle and split optimization for single or coupled intersections under the same controller. PLATO has been demonstrated in both software-in-the-loop, hardware-in-the-loop, and in-house tests with real-world data from Edmonton, Alberta. The architecture of PLATO (Figure 15) lends itself conveniently to the proposed project because the control decision from DNB will be translated into the NTCIP command (green hold/force-off as the key ones) to influence the signals at the target intersections. Meanwhile, this software-based ‘plug-and-play’ architecture will benefit from the standard controllers’ malfunctioning management units and other fail-safe design features; when the tests are completed, the new system will return the control to the signal system for normal operations.

Data Acquisition Systems (DAS) Development

ERL personnel have the ability to connect and decode all vehicle signals. Vehicles are equipped with more than 100 computers, which are all networked. The ERL will install Flexray, LIN, and CAN reading equipment, which will be connected to a WiFi-enabled PC. This PC will decode the relevant signals (subset) and communicate them via the In-vehicle WiFi to the cloud server. The required signals will include the following instantaneous data: a Network Time Protocol (NTP)-synced timestamp, vehicle velocity, vehicle acceleration, GPS data, engine gear, engine torque, engine speed, fuel consumption, and positions and speeds of surrounding vehicles. To protect driver privacy, these signals will only be recorded along the designated test arterials.

Field Demonstrations

Proposed Test Sites

Two field test sites will be used for this project, namely: an arterial roadway in the Blacksburg/Christiansburg, VA area and a section along either US route 29 or 50 in the Northern Virginia area. The Blacksburg/Christiansburg test site is an arterial corridor connecting the towns of Blacksburg and Christiansburg to various shopping outlets. The section is very highly traveled and includes a total of 11 signalized intersections managed by VDOT, as shown in Figure 16. Given that this local roadway has various traffic demand levels (high traffic volumes during peak hours and low traffic volumes during non-peak hours) and signal timing plans (traffic-responsive actuated signals), it will be used as the main test site in this project. The team will spend six months at the Blacksburg/Christiansburg test site to collect data, implement, field test, and demonstrate the proposed system, by following the proposed experimental design (Figure 18).

Figure 15: Communication to traffic signal controller for second-by-second control decision update

The Northern Virginia test site (Figure 17) also has multiple VDOT-managed signalized intersections along US 29 and US 50. An arterial roadway in this area will be selected for the final demonstration to showcase the developed system. In the final demonstration, we will compare the CAV system with the proposed controllers to the fully integrated CAV-TSC system. It should be noted that all the researchers who operate the test vehicles will complete a training program with ERL in Arizona to ensure that researchers can correctly and safely take control of the CAVs if and as needed.

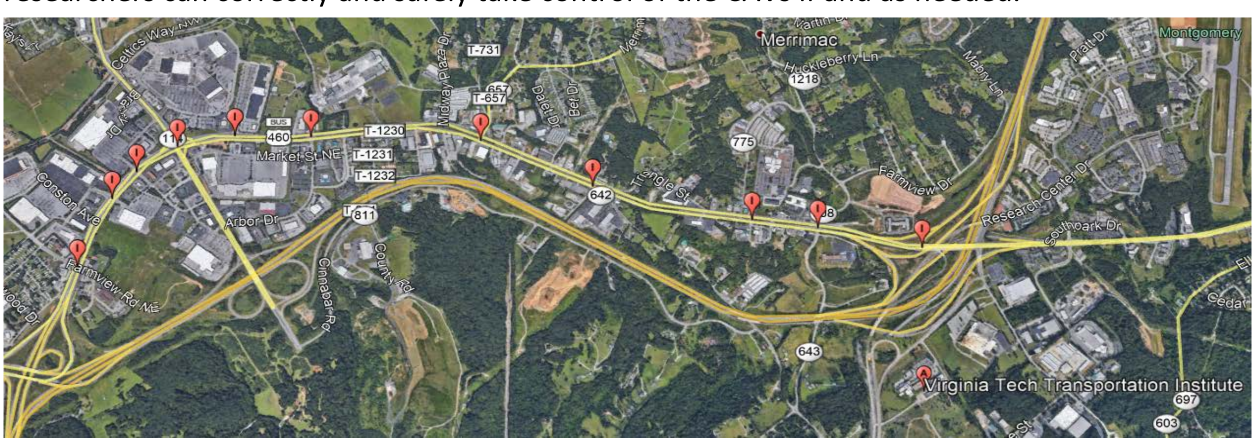


Figure 16: The layout of the Blacksburg/Christiansburg, VA test site with multiple signalized intersections (source: Google Maps)

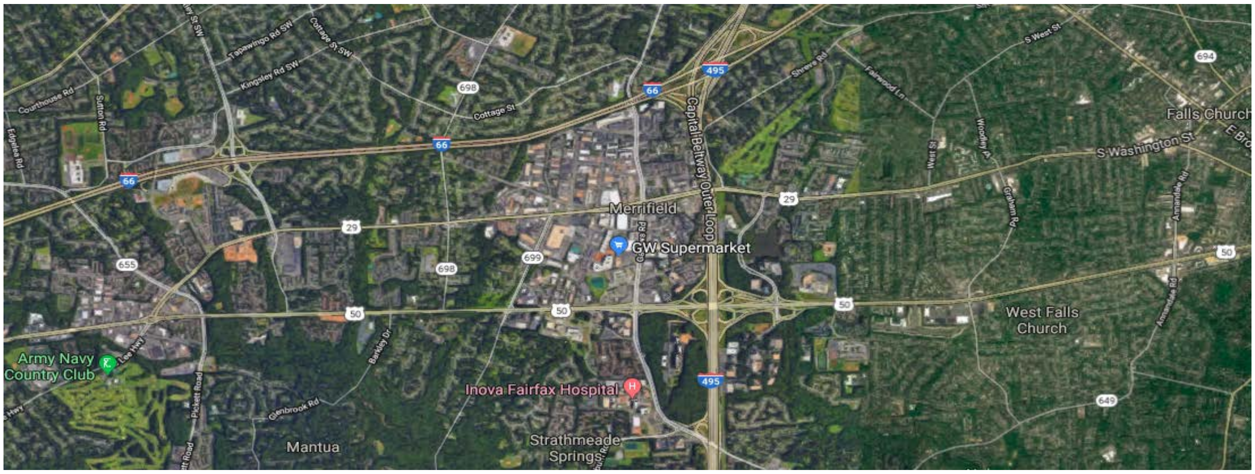


Figure 17: Layout of Northern Virginia test site on US 29 and US 50 (source: Google Maps)

Design of Experiments

The field test will investigate the effects of three factors, the test vehicle, the traffic signal controller, and the traffic signal indication, on traffic safety, mobility, and energy efficiency of both the vehicles and the system. Different experimental approaches will be considered for the field test to ensure the data obtained yield valid and objective conclusions. The simplest option is to randomly assign each factor for each test trip when a test vehicle passes each signalized intersection. However, there are practical constraints to consider when randomly changing each factor during field testing. Firstly, there are safety concerns associated with randomly switching vehicle control between non-CAV and CAV control along a test trip. Secondly, the traffic signal controller strategies may not be easily changed for each test trip. Considering these constraints, a split-split plot design will be used to evaluate the system performance. The split-split plot design is a restricted randomization experimental design originally proposed in the field of agriculture to make the experiment design easier and more cost and time effective [39]. The split-split plot design in this project is a blocked experiment with three levels of experimental units, as demonstrated in Figure 18. The first level of the experimental units is the whole plot (test vehicle) including non-CAV, existing CAV controllers, and CAV with the proposed controllers. The second level is the experimental units within the whole plot, called the split plot (signal controller); which consists of fixed-timing, actuated and DNB control strategies. The third level is the experimental units within the split plot, called the split-split plot (traffic signal indication) including different signal indications of green, yellow and red. Note that the effect of the test vehicle (variation in driving behavior among test vehicles) will be considered as a random effect; thus, it will not be used as a fixed-effect factor. Statistical analysis will be conducted to quantify the benefits of using the proposed controllers for traffic safety, mobility, and energy efficiency under different traffic signal control strategies and traffic signal indications.

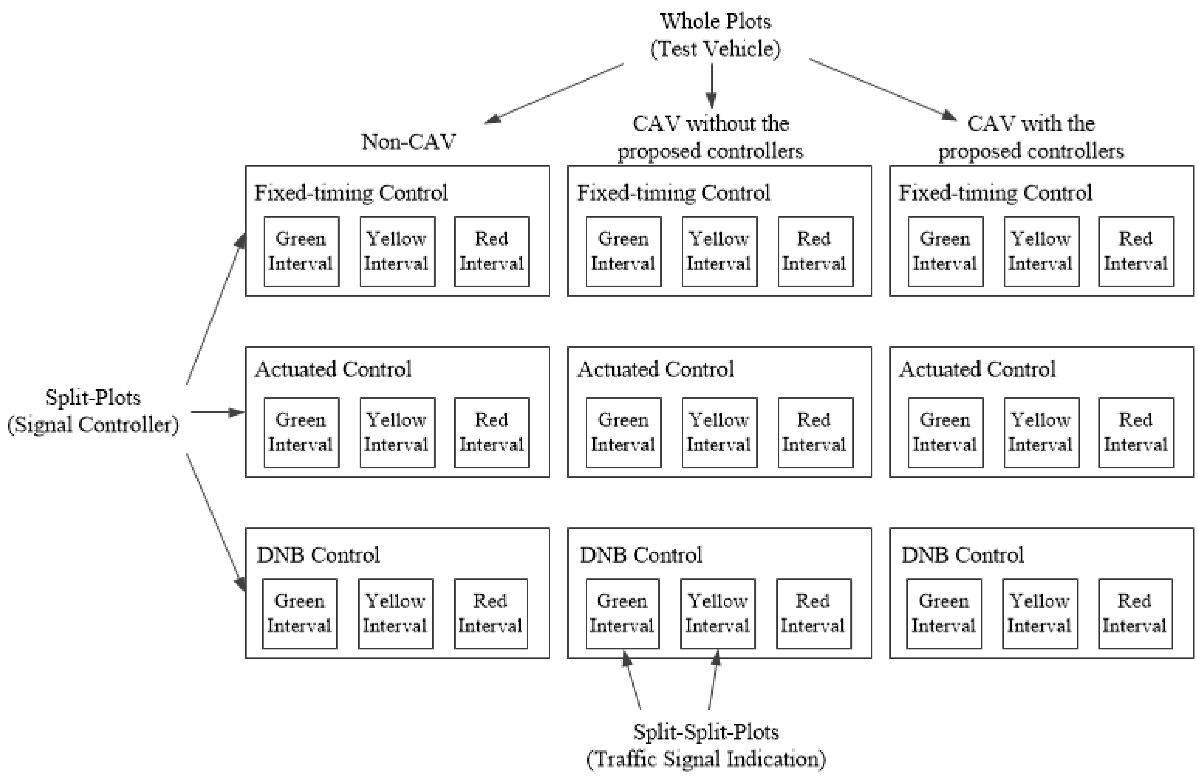


Figure 18: Proposed experimental design for phase 2 field testing

Safety Evaluation

Prior to field testing on public roads, we will test the proposed CAV and CAV-TSC systems on controlled test facilities including VTTI's Smart Roads and VW's testing facilities. The tests on the closed test facilities will allow us to validate the CAV and CAV-TSC systems and to stage various driving situations that can occur on the real roads during the field testing.

The team will perform a safety evaluation of the proposed CAV and CAV-TSC systems during the field tests. The safety evaluation will entail the following analyses:

1. We will perform a wide variety of individual tests on our test facilities for competencies that are relevant to signalized intersections. The behavioral competencies that will be considered for field testing include 1) detect and respond to speed limit changes and speed advisories; 2) detect and respond to encroaching oncoming vehicles; 3) perform car-following (including stop-and-go); 4) detect and respond to stopped vehicles; 5) detect and respond to lane changes; 6) detect traffic signals and stop/yield signs; 7) respond to traffic signals and stop/yield signs; and 8) navigate intersections and perform turns.
2. We will evaluate the car-following behaviors of the CAV and surrounding non-CAV vehicles to quantify the system-wide safety impacts of CAVs. This could be derived using crash surrogate measures including time-to-collision, as was done in evaluating the safety impacts of a forward collision warning system [40]. Specifically the team will compare and evaluate the time-to-collision data for non-CAV and CAV controls using sensor data and will estimate crash risks for both controls.
3. We will investigate the trajectory noise, extent of shockwaves, and speed of waves to quantify overall intersection safety measures.

4. We will analyze any events that needed driver intervention and driver taking control of the CAVs. This type of analysis would be similar to previous work we did in evaluating the safety impacts of adaptive cruise control systems [41].
5. We will compare CAV and non-CAV vehicle behavior during yellow intervals. This will include the number of yellow light runs, the deceleration level associated with stopping, driver PRTs versus system latencies, the number of correct and incorrect stop/go decisions, and red light violations.
6. Given that the crash risk is computed as the crash rate multiplied by the temporal exposure, as was demonstrated in a model we developed earlier [42], the crash risk will only be a function of the time the vehicles spend on the network given that the crash rates remain the same for the CAV and non-CAV scenarios. Consequently, reducing delay would result in a direct reduction in the crash risk given that vehicles would be traveling on the same facilities (i.e. would have the same crash rate).
7. We will evaluate the behaviors of our test vehicles at all conflict points in signalized intersections. The test vehicles will be equipped with various sensors including multiple 360-degree environment cameras, long and mid-range radars, Lidar system, and sonic sensors. The team will carefully evaluate the possible safety conflicts during the field tests based on video data and other sensor data. In particular, we will investigate the behavioral changes for non-CAV (human driving) and CAV controls at intersections and evaluate the performance of both non-CAV and CAV controls for a variety of operational scenarios.

Legal and Regulatory Review

The Commonwealth of Virginia has made a conscious decision not to pass any laws or develop regulations related to CAV operations in the Commonwealth. All laws and regulations related to human-operated vehicles apply to CAV operations. As such, the regulatory framework for the testing of CAVs in the Commonwealth of Virginia is very simple. As long as a human safety driver responsible for the vehicle's operation is behind the wheel of the vehicles during the testing periods, and the project team follows all general laws, insurance, licensing, and registration requirements for the vehicles, the CAV field tests and demonstration can be conducted on the roadways identified for this project or any other public roads in the Commonwealth.

In addition, the test drivers who will be responsible for the vehicle operation will undergo rigorous training at VW facilities in Arizona. This training will provide the drivers with sufficient knowledge and expertise to operate the vehicle in the event that their intervention is needed. Finally, as mentioned earlier, the team includes VDOT, who will also oversee the ADS demonstration.

Project Tasks and Timeline

The project is divided into three phases, each containing specific tasks, as shown in Figure 19. The first phase entails adding the real-time queue prediction logic to GLOSA, adding background traffic, and running some controlled tests at ERL's facility in Belmont, CA. This phase is scheduled to end six months after the start of the project (12/31/2019, assuming a start date of 7/1/2019). The second phase involves developing all control algorithms for the vehicle (CAV system) considering actuated and traffic responsive control. This phase will conclude with the first demonstration in the Blacksburg/Christiansburg, VA area at 24 months after the start of the project. The field demonstration and testing will last for six months. The third and final phase involves integrating the traffic signal control with the vehicle control to develop the fully-integrated CAV-TSC system. This fully integrated CAV-TSC system will be field-tested and demonstrated 36 months from the start of the project. The field testing will initially be conducted in Blacksburg/Christiansburg, VA and then demonstrated in Northern Virginia. The output from these field tests will be analyzed and summarized in the final six months of the project.

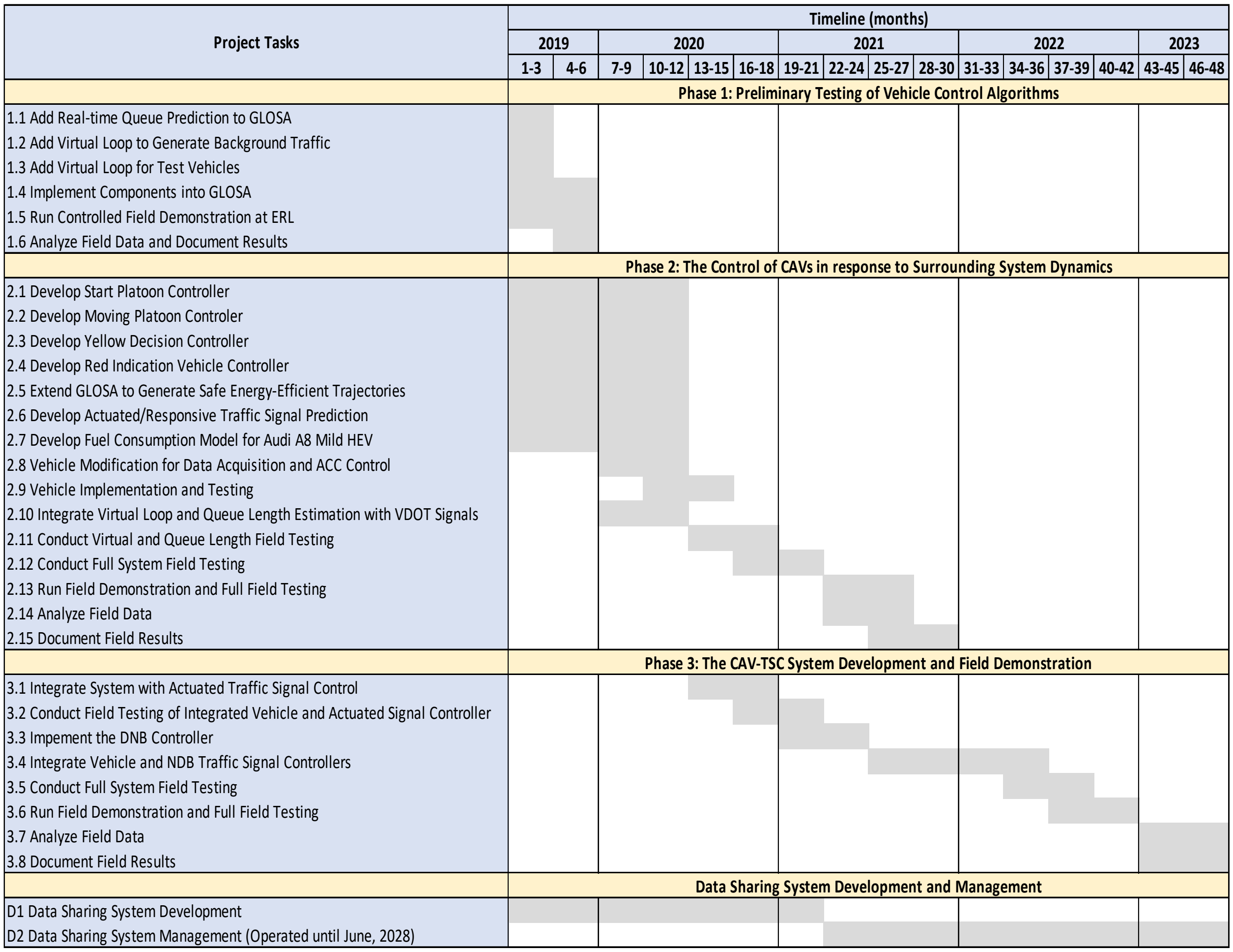


Figure 19: Project tasks and timeline.

Risk Management

The team has identified potential technical, regulatory, and management risks. These risks, along with the team's corresponding preliminary mitigation strategies, are summarized in Table 1.

Table 1: Potential Risks and Mitigation Strategies

#	Category	Risk Description	Mitigation Strategy
1	Technical	Communication errors lead to loss of communication data and latencies	Fallback strategies will be developed to check communication errors, ensuring a robust system. Fallback control strategies will be identified and incorporated.
2	Technical	Lack of real-time data and/or low data quality	The team will develop a procedure to determine the completeness and integrity of traffic and CAV data and develop models to impute incomplete data.

3	Technical	Delays in real-time computation that negatively affect system performance	The team will develop an efficient algorithm to improve the computational speed.
4	Technical	Fully integrated ADS system generates errors due to computational complexity and conflicts between the various system components.	The team will evaluate the system's compliance and verify the interactions among the modules of ADS to detect possible errors and improve performance.
5	Technical	Cyber security of ADS	The team will prepare threat analysis that maps its vulnerabilities and assesses the level of risk.
6	Technical	Data security	The team will separate the database and web servers and will encrypt stored files.
7	Technical	ADS operational failure	The team will review the ADS safety elements before field tests including system safety, Operational Design Domain (ODD), Object and Event Detection and Response (OEDR), Fallback strategies, and Human Machine Interface
8	Regulatory	Failure to obtain necessary approvals for field testing from the relevant agencies	The team will utilize and expand its partnerships with local agencies, including regional transportation agencies and local law enforcement agencies.
9	Manage-ment	Risks associated with the project schedule	The team leaders will track the progress of the project to ensure that no delays are incurred. If delays are encountered during some tasks along the critical path, adjustments will be made to the schedule by allocating additional resources to future tasks or by running some tasks in parallel. If project changes are required, the team will consult with DOE project managers to develop mitigation strategies.
10	Manage-ment	Exceed the project budget or project timeline	The team will use a proactive management approach and the proposed work plan covering all major activities to provide DOT with timely, reliable, secure, and compliant results.

Cost Sharing

The total cost of the proposed effort is $4,955,178. This includes a total Federal share of $3,328,708 (67% of the total cost) and a non-Federal share of $1,626,470 (33% of the total cost). The cost share provided by VTTI will cover a portion of Dr. Rakha's time (5% over the duration of the project) and the cost associated with the data sharing system development and management ($441K). ERL will contribute $915,000 in engineering support, travel, driver safety training, materials and supplies, and two Audi vehicles with data interface equipment and ACC control. TTS will provide a cost share of $267,500 to cover one Personal Signal Assistant® R&D Account; which includes access to the Personal Signal Assistant® cloud services and its MAP and SPaT data; one dedicated server within the TTS data center; allocated support hours from engineering, software development, operations and support teams; and travel. VDOT will provide $3,180 in cost share in person labor to assist with the ADS demonstration and field implementation. A more detailed breakdown of the budget by task and year is provided in the cost section of the proposal.

References

1. U.S. Department of Transportation, *Transportation Statistics Annual Report 2018*. 2018. Bureau of Transportation Statistics: Washington D.C.

2. U.S. Department of Transportation, *Preparing for the Future of Transportation - Automated Vehicles 3.0*. 2018: Washington, D.C.
3. U.S. Department of Transportation. *Intersection Safety*, 2018 [cited 2019 Feb. 20]; Available from: https://highways.dot.gov/research-programs/safety/intersection-safety.
4. Wu, L.N., et al., *The Influence of Intersections on Fuel Consumption in Urban Arterial Road Traffic: A Single Vehicle Test in Harbin, China.* PLoS One 2015, **10**(9).
5. Amer, A., H. Rakha, and I. El-Shawarby, *Novel Stochastic Procedure for Designing Yellow Intervals at Signalized Intersections.* J. Transp. Eng. 2012, **138**(6), 751-759.
6. Bryant, C.W., H.A. Rakha, and I. El-Shawarby, *Study of truck driver behavior for design of traffic signal yellow and clearance timings.* Transport. Res. Rec. 2015, 2488, 62-70.
7. Ong, B.T., H.A. Rakha, and I. El-Shawarby, *Design of Traffic Signal Clearance Intervals to Consider Impacts of Buses.* Transport. Res. Rec. 2015, 2492, 33-45.
8. Elhenawy, M., I. El-Shawarby, and H. Rakha, *Modeling the Perception Reaction Time and Deceleration Level for Different Surface Conditions Using Machine Learning Techniques*, in *Advances in Applied Digital Human Modeling and Simulation*. 2017, Springer International Publishing. p. 131-142.
9. El-Shawarby, I., A.-S.G. Abdel-Salam, and H. Rakha. *Evaluation of Driver Perception-Reaction Times for Rainy and Wet Roadway Conditions at Onset of Yellow Indication at Signalized Intersections*. Transport. Res. Rec. 2013, 2384, 18-24.
10. Li, H., H. Rakha, and I. El-Shawarby, *Designing Yellow Intervals for Rainy and Wet Roadway Conditions.* Int. J. Transport. Sci. Tech. 2012, **1**(2), 171-190.
11. Elhenawy, M. et al. *Modeling driver stop/run behavior at the onset of a yellow indication considering driver run tendency and roadway surface conditions.* Acc. Anal. Prev. 2015, **83,** 90-100.
12. Dehkordi, S., et al., *Ecological and safe driving: A model predictive control approach considering spatial and temporal constraints.* Transp. Res. D 2019, **67,** 15.
13. Kamalanathsharma, R.K. and H.A. Rakha, *Fuel-Optimal Vehicle Throttle Control: Model Logic and Preliminary Testing*. 20th ITS World Congress, 2013.
14. Kamalanathsharma, R.K. and H.A. Rakha, *Leveraging Connected Vehicle Technology and Telematics to Enhance Vehicle Fuel Efficiency in the Vicinity of Signalized Intersections.* J. Int. Transport. Sys. 2016, **20**(1), 33-44.
15. Rakha, H. and R.K. Kamalanathsharma, *Green Cooperative Adaptive Control Systems in the Vicinity of Signalized Intersections*. TranLIVE, University of Idaho, 2014 (No. N14-19).
16. Kamalanathsharma, R.K. and H.A. Rakha. *Multi-stage dynamic programming algorithm for eco-speed control at traffic signalized intersections*. In *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, 2013, pp. 2094-2099, IEEE.
17. Kamalanathsharma, R.K. and H.A. Rakha. *Fuel-Optimal Vehicle Throttle Control: Model Logic and Preliminary Testing*. In 20th ITS World Congress, 2013.
18. Almannaa, M.H. et al., *Controlled-Field Evaluation of Effectiveness of Infrastructure to Vehicle Communication in Reducing Vehicle Fuel Consumption and Delay at Signalized Intersections*. 96th Annual TRB Research Board Meeting, Washington, D.C., 2017.
19. Almannaa, M. et al., *Field implementation and testing of an automated eco-cooperative adaptive cruise control system in the vicinity of signalized intersections.* Transp. Res. D, 2019, **67,** 19.

20. Yang, H., H. Rakha, and M.V. Ala, *Eco-Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects.* Trans. Intell. Transp. Syst. 2016, **18**(6), 1575-1585.
21. Abdelghaffar, H.M. and H.A. Rakha, *A Novel Game Theoretic De-centralized Traffic Signal Controller: Model Development and Testing*. In 97th TRB Annual Meeting, 2018.
22. Abdelghaffar, H.M., H. Yang, and H.A. Rakha, *Developing a De-centralized Cycle-free Nash Bargaining Arterial Traffic Signal Controller*. In 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, Napoli, Italy, 2017.
23. Abdelghaffar, H.M., H. Yang, and H.A. Rakha, *Isolated Traffic Signal Control using Nash Bargaining Optimization.* Global J. Res. Eng. 2017, **16**(1).
24. Abdelghaffar, H.M., H. Yang, and H.A. Rakha. *Isolated traffic signal control using a game theoretic framework*. In 19th IEEE International Conference on ITS (ITSC), 2016, IEEE.
25. Badillo, B.E. et al. *Queue length estimation using conventional vehicle detector and probe vehicle data*. In 15th International IEEE Conference on ITS (ITSC), 2012, IEEE.
26. Chen, H. et al., *Development and Preliminary Field Testing of a Connected Vehicle Eco-Speed Control System in the Vicinity of Signalized Intersections.* In 14th IFAC Symposium on Control in Transportation Systems (CTS 2016), May 18-20, 2016, Istanbul, Turkey, 2016.
27. Ahn, K., H. Rakha, and S. Park. *ECO-Drive Application: Algorithmic Development and Preliminary* Testing. TRB Journal 2013, 2341, 1-11.
28. Daganzo, C.F. and R.C. Garcia, *Pareto improving strategy for the time-dependent morning commute problem.* Transp. Sci. 2000. **34**(3), 303-311.
29. Sheffi, Y. and H. Mahmassani, *A Model of Driver Behavior at High Speed Signalized Intersections.* Transp. Sci. 1981, **15**(1), 50-61.
30. Rakha, H., K. Ahn, and R.K. Kamalanathsharma, *Eco-vehicle speed control at signalized intersections using i2v communication.* USDOT, Tech. Rep, 2012.
31. Kamalanathsharma, R.K. and H. Rakha. *Agent-based modeling of Eco-Cooperative Adaptive Cruise Control systems in the vicinity of intersections*. In 15th International IEEE Conference on Intelligent Transportation Systems (ITSC), 2012, IEEE.
32. Rakha, H. and R.K. Kamalanathsharma. *Eco-driving at signalized intersections using V2I communication*. In 14th International IEEE Conference on ITS (ITSC), 2011, IEEE.
33. Kamalanathsharma, R.K., H.A. Rakha, and H. Yang. *Networkwide Impacts of Vehicle Ecospeed Control in the Vicinity of Traffic Signalized Intersections.* Transp. Res. Rec. 2015, 2503, 91-99.
34. Yang, H., M.V. Ala, and H.A. Rakha. *Eco-Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects*. In TRB 95th Annual Meeting, 2016.
35. Ala, M.V., H. Yang, and H. Rakha. *A Modeling Evaluation of Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections*. In TRB 95th Annual Meeting, 2016.
36. Chen, H., et al., *Development and Preliminary Field Testing of an In-Vehicle Eco-Speed Control System in the Vicinity of Signalized Intersections*. In 14th IFAC Symposium on Control in Transportation Systems, Istanbul, Turkey, 2016.
37. Chen, H., et al., *Development and Field Testing of an Eco-Speed Control System at Signalized Intersections*, In 20th ITS World Congress, Melbourne, Austrailia, 2016.
38. Jones, B. and C.J. Nachtsheim, *Split-plot designs: What, why, and how.* J. Qual. Tech. 2009, **41**(4), 340-361.