Clemson-Center of Excellence for Automated Driving Systems

Submitted By:
Clemson University

In Response To:

U.S. Department of Transportation
NOFO Number 693JJ319NF00001
“Automated Driving System Demonstration Grants”

March 2019

PART 1 – PROJECT NARRATIVE AND TECHNICAL APPROACH

Secretary Elaine Chao
Secretary of Transportation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

Acting Director Aimee Drewry
Acting Director, Office of Acquisition and Grants Management
Federal Highway Administration
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

Dear Secretary Chao and Acting Director Drewry,

Clemson University is pleased to submit this application in response to U.S. Department of Transportation (DOT) Notice of Funding Opportunity (NOFO) for Automated Driving System (ADS) Demonstration Grants (NOFO Number 693JJ319NF00001). The assembled team, which includes the Carolinas Alliance 4 Innovation, the Center for Transportation and the Environment, and the University of South Carolina represents public and non-profit regional partners. The proposal has the support of the SC Departments of Transportation, Public Safety, Motor Vehicles and Insurance, the Cities of Greenville and Mauldin, SAE International, ITIC- a test track facility, and partner automation companies such as New Eagle, Autonomous Stuff, NVIDIA, KVA functional safety, and Ford, the OEM for our transit vehicles. Please see Part 4 of the application for a complete list of all the letters of support provided for this application.

The automotive cluster in upstate South Carolina employs 4.6 times the concentration in the U.S. overall, and supports a 3.3 percent annual employment growth. Clemson University has made huge contributions to this growth with its unique automotive-oriented research and education programs and is poised to make even more impact by advancing research for safe and efficient mobility for all, with connected and automated vehicles. It is, therefore, with great enthusiasm that we respond to this NOFO as it squarely aligns with our priorities. The University and its partners have assembled the expertise and collaborations needed for a successful and open ADS demonstration effort that will inform standards and rulemaking and meet DOT's expressed goals.

Clemson is requesting ~$8.5m of federal funds to support this effort, with a contribution of non-federal cost share in the amount of ~$1.55m.

On behalf of Clemson, our team members, and supporters from throughout the state, I would like to thank you for your consideration of our application for funding under this NOFO. We appreciate the US DOT's commitment to advancing the integration of ADS into the nation's transportation system.

If you have any questions regarding Clemson's application, please contact me at terryr@clemson.edu or 864-656-5533.

Sincerely,

Terry H Rumph Terry Rumph, Grants Administrator, Clemson University

SUMMARY TABLE

Summary Table	
Project Name/Title	Clemson-Center of Excellence for Automated Driving Systems (C-CEADS)
Eligible Entity Applying to Receive Federal Funding (Prime Applicant's Legal Name and Address)	Clemson University
Point of Contact (Name/Title; Email; Phone Number)	Terry Rumph, Grants Administrator terryr@clemson.edu 864.656.5533
Proposed Location (State(s) and Municipalities) for the Demonstration	Cities of Greenville and Mauldin, South Carolina
Proposed Technologies for the Demonstration (briefly list)	
Proposed duration of the Demonstration (period of performance)	4 years (July 2019-June 2023)
Federal Funding Amount Requested	$8,497,777
Non-Federal Cost Share Amount Proposed, if applicable	$1,548,200
Total Project Cost (Federal Share + Non-Federal Cost Share, if applicable)	$10,045,977

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PART 1 – PROJECT NARRATIVE AND TECHNICAL APPROACH

1. EXECUTIVE SUMMARY

a) Vision, Goals and Objectives: Clemson University seeks to establish a Center of Excellence for Automated Driving Systems (ADS) by leveraging this proposed US DOT demonstration project, as well as the University's and the State of South Carolina's already committed resources for a premium automotive research and education enterprise in the Southeast. Despite their potential for reducing crashes and improving mobility, ADS technology has yet to be sufficiently evaluated on public roads to be afforded a high level of trust of their safety by all stakeholders: users, industry, and regulators. Our **vision** for the proposed project is to demonstrate driving policies that verify the safety of ADS in representative operational environments. Our vision for the project also responds to DOT's expressed need for *open exchange of data* about ADS operating experience among stakeholders to foster public understanding of the technology. Given this vision, the project's **goals** are to: 1) Integrate and demonstrate two vehicles with ADS systems that would achieve SAE Level 3 conditional automation; 2) Evaluate driving policies and perception modules implemented on ADS in various settings including a new Vehicle-In-the-Loop approach and controlled traffic settings on a closed test track and open-road demonstrations; 3) Deploy next generation connected vehicle safety applications by upgrading an existing DSRC and LTE-based connected vehicle test-bed at Clemson with emerging 5G technology and heterogenous network management; 4) Provide access to detailed on-board ADS granular operational data as well off-board external monitoring data for ADS operating in mixed-traffic for further behavioral analysis. To achieve these goals, Clemson will work with its industry partners to integrate automation capabilities on two transit vehicles that seat 12-15 passengers. The team will then conduct phased demonstrations of the ADS in typical suburban traffic scenarios, progressing from light traffic to more complex domains and culminating in the transit use cases around a loop in Mauldin, SC. The team will leverage 5G infrastructure as it deploys in subsequent years by upgrading the current CV test bed.

b) Key Partnerships: The key partners in this project are Clemson University (lead), International Transportation Innovation Center (ITIC), Center for Transportation and the Environment (CTE), New Eagle (Drive By Wire supplier), Autonomous Stuff (automation integrator), SAE International, KVA- functional safety consultants, PTV VISSIM (traffic software vendor), Carolina Alliances 4 Innovation (CA4I), the University of South Carolina, South Carolina Department of Public Safety (SCDPS), South Carolina Department of Transportation (SCDOT), South Carolina Department of Insurance (DOI), the City of Greenville and the City of Mauldin.

c) Issues and Challenges: The first challenge is that SAE Level 3 ADS capabilities are not currently readily available in a manner that allows open access to on-board operational data. To overcome this challenge, Clemson will purchase two vehicles and have them professionally retrofitted with automation capabilities, so the project team can advance to demonstration work as safely and as quickly as possible. Another challenge is the lack of current ADS safety evaluation test procedures, regulations and standards, particularly at Level 3 and higher. To mitigate risk, developers often specify operational design domains (ODDs) and test only to that domain. As a potential workaround on this lack of openly available knowledge on "how to test ADSs" or "what to test them to?" the Clemson team will use VIL simulations and closed test track experiments as low safety risk approaches to identify critical traffic scenarios to test to and identify accompanying ADS safety measures. The most significant challenges are posed by conducting demonstrations and experiments on open roads in terms of public safety risks. To address them, we will rely on close collaboration with local governments, SCDPS, and SCDOT to coordinate the planning and execution of the demonstrations to assure safety. We have also enlisted SAE International as a close collaborator, through which we will exchange test procedures and scenarios with other parties and contribute data and findings towards standards and rulemaking.

d) Geographic Area for Demonstration: All physical ADS demonstrations will be conducted at the ITIC test track and on public roads in Greenville, SC. The proposed final use case demonstration includes shuttle/transit service in Mauldin, SC, a suburb of Greenville.

e) Proposed Period of Performance and Schedule: The proposed performance period is four years (2019-2023). The details and timelines for the components of each major task are included in Part 2 -Management Approach, of this submission.

	Major Task Category	2019		2020				2021				2022				2023	
Task		Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1	Vehicle Platform Hardware/Software Integration		■	■	■	■	░										
2	Build Demonstration Support Infrastructure		■	■	■	■	■										
3	Conduct ADS Demonstrations on Identified Domains					■	■	■	■	■	■	■	■	■	■	■	
4	Stakeholder Engagement			■			■			■		■		■	■	■	■
5	Project Management, Reporting	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 1 Project schedule and timelines- overview

2. GOALS

A. SAFETY

This project will directly address challenges facing the safe integration of automated driving systems (ADS), via demonstrations derived from use cases that are representative of America's on-road transportation system. Crash causation data and analysis from NHTSA show that human-driver errors account for more than 90% of roadway accidents[1]. Proponents of ADS often argue that using this technology to remove or relieve humans from part or all of the driving task will significantly reduce highway crash incidents. However, the integration of vehicles with ADS into the legacy roadway system, with its infrastructure, rules, and customs designed for human drivers, requires overcoming immense challenges. Some of these challenges are technical in nature. The ADS vehicles must have robust perception (means for object and event detection and response (OEDR)), decision-making, motion planning, and vehicle dynamics control systems that ensure behavioral competencies consistent with expectations of other road users. Lack of sufficient experience operating ADS on public roads, as well as the competitive value assigned to mostly privately acquired data, has made it difficult to publicly examine challenges of integrating ADS on our roadways, and to offer robust approaches for addressing them. This lack of data feeds other challenges such as lack of baseline for standards and regulations.

In this project, we aim to extract *driving policies* for ADS that ensure safety to all participants and property during some common – yet challenging – scenarios involving interactions between ADS vehicles and other road users. These driving policies manifest as design requirements/settings for the ADS perception/OEDR, decision-making, motion planning and control modules that may eventually inform standards and regulations. To accomplish this in a timely and cost-effective manner, we outline approaches for accelerated generation of safety-critical scenarios and their evaluation with minimal public safety risk.

B. DATA FOR SAFETY ANALYSIS AND RULEMAKING

Data Gathering and Sharing: We will provide vast safety-relevant data generated by the ADS-equipped vehicles. These data will be collated by demonstration scenarios, and will range in variety from raw sensor data (e.g. lidar point clouds) to fused outputs of the perception modules (object detections, tracks), control actuation signals, on-board diagnostic information, ADS disengagements, and closed-loop responses (accelerations, velocities, trajectories, jerk profiles). Furthermore, in our demonstrations, we will install traffic observer stations that can provide *objective/'ground-truth'* behavioral data about the ADS vehicle and other traffic participants. These stations allow us to detect, classify, label, and track objects with detailed kinematic information that can subsequently be used to assess the behavioral competencies of the ADS.

Commitment to Leveraging Demonstration Data and Results. We plan to maximize the utilization of the data we generate by all ADS and traffic safety researchers by making it readily accessible online and user-intuitive. The variety in the granularity of the open data this project allows researchers to focus on aspects of ADS integration that need further investigation. For example, trajectory data collected in prototypical scenarios can be used to evaluate various driving policies, and raw sensor data can be used for evaluating/developing different OEDR algorithms. Some such evaluations are integral parts of our project activities. Furthermore, we have recruited the direct support of SAE International to engage in standards development, to host demo day events for the public and policymakers, and to promote utilization of the data by its global membership via workshops, symposia and conference participation.

Data and Information to Identify Risks, Opportunities and Insights for Rulemaking. The demonstrations will provide on-board and external data on important measures relevant for characterizing the safety risk of ADS integration into the transportation system. A broad grouping of these measures is as follows: 1) infraction incidents, 2) roadmanship measures, 3) disengagements of the ADS, and 4) lagging outcome measures such as crashes with severe injury (per 100,000 miles)[2]. The first two are proxy measures that link to *risks of collision* of ADS vehicles with other road users. Examples of infractions include right-of-way violations such as failure to yield and disobeying traffic signals. Roadmanship measures assess ADS vehicle safety in avoiding hazards during interactions with other road users. A summary of several roadmanship metrics is given in Refs[2], [3]. Examples of the metrics that can be computed with the technology we deploy (all sensors and subsequent processing) include variations of the following: Rapid acceleration/deceleration (jerk) profile and yaw rate, Time/distance to Collision, post-encroachment time, on-board computable metrics such as probabilities of collision (crash propensity using online prediction models as done in our work in [4] or in [5]), and *safety envelope* violation. The last of these is especially relevant for ADS integration on public roads since safety boundaries need to be defined around the ADS vehicle (in time, given speed, or in space, or around infrastructure) for all situations in its ODD that demand appropriate evasive actions. The safety envelope is defined by behavior rules embedded in the ADS relating to safe around ego-vehicle in all relevant directions (lateral, longitudinal), selecting maneuvers that respect and give (not take) right of way, and accounting for sensor limitations (such as occlusions). Counts of the safety envelope violations measure the vehicles ability to follow rules of the road, but the concept can be extended to assign responsibility to all road users (including the ADS vehicle)[6] and are therefore candidate metrics for rulemaking for ADS integration in public traffic. ADS disengagement is now a major (if not the only) reported safety metric in California by all ADS developers testing on public roads in that state[7]. We will follow similar reporting protocols in our demonstrations, though we recognize disengagements are less reliable as objective safety metrics than observed infractions and roadmanship.

Existing state and federal regulations generally assume the presence of a human driver. The advent of ADS requires a different look at new safety risks to vehicles that are otherwise fully compliant to current FMVSS; an FMVSS compliant ADS vehicle could still cause a crash due to uncertainties associated with any of its main automation modules. A new or extended safety paradigm is needed that mandates safety performance requirements for ADS[8]. This paradigm should require, for example, procedures for verifying how and what safety envelopes are assured for ADS interactions with other road users of different categories - cars, heavy trucks, bicycles or pedestrians. These are not unlike certain state DMV laws that prescribe such requirements for human drivers, but with highly automated vehicles, the ADS is an integral part of the vehicle and such requirements have yet to be established.

The proposed demonstrations will generate data on prototypical and worst-case scenarios involving integration of ADS on public roads. The performance data and the *driving policies exercised in these scenarios will help set baselines* for regulations and standards on these prototypical scenarios. Some of our proposed accelerated testing mechanisms will also allow safe experimentation on rare/edge cases that are difficult to come by with exposure-oriented road testing for several thousands of miles. The granular operational data (on-board and off-board) *can help provide insight* into the correlation of specific leading safety measures (infractions, roadmanship, disengagements) and lagging ones such as crashes and fatalities. The granular data will also include information about the *interaction of the ADS with different road user categories*. That is, the data can give insight into how our ADS equipped transit vehicles and their motion physics are perceived by and reacted to by other road users; pedestrians, light vehicles and heavy commercial vehicles. Analyses of these interactions can help define a degree of *safety equivalency*, although our scope doesn't explicitly include ADS for the other weight categories.

C. COLLABORATION

This project assembles a diverse group of partners and other participants from the public, private, and non-profit sectors. Clemson University is leading the project with faculty housed both at its main campus in Clemson, and its satellite Center for Automotive Research (CU-ICAR) campus in Greenville. The project will leverage the automotive engineering and computer science talent developed at Clemson, and additional resources offered by South Carolina's Upstate automotive cluster, including the South Carolina Technology and Aviation Center's (SC-TAC) International Transportation Innovation Center (ITIC) test track. This industry cluster is exemplary of Clemson's existing collaboration with both government and leading automotive firms and serves as a foundation for future excellence in automated vehicle engineering.

The Carolinas Alliance 4 Innovation (CA4I), an economic development nonprofit staffed by current and former Greenville elected officials, and business leaders, has organized project participation and support from multiple private and public agencies. These include the County of Greenville, the Cities of Greenville and Mauldin, SCDOT, and the South Carolina Departments of Public Safety, Insurance, and Motor Vehicles. Continuous communication between the Clemson-led team and these stakeholders over the course of the project period will ensure the demonstration maintains continued political support and informs the public and policymakers on ADS safety and other benefits. Mauldin's assistance in supporting the final phase of the demonstration will help the project team collect data on its transportation-challenged senior citizens, which the team sees as a candidate population for the shuttle service demonstrated.

The Center for Transportation and the Environment (CTE) will manage and advise the project components, bringing its 27 years of experience on similar federally-funded transportation technology demonstration programs. Finally, Clemson, ITIC, CA4I, and CTE will leverage their relationships with the Society of Automotive Engineers (SAE) and IEEE to communicate demonstration findings and inform standards development.

3. FOCUS AREAS

A. SIGNIFICANT PUBLIC BENEFITS

This project would produce significant public benefits in *three* key areas: First, the multi-year demonstration would collect large amounts of safety-relevant data for policymakers with no proprietary restrictions. Most of the current ADS deployments, whether purely private or part of a private-public partnership, have generated little performance data for public consumption. The disengagements reporting required by California for ADS developers testing on public roads has produced unstandardized data with limited utility for policymakers. The data proposed to be collected in this project would involve much greater detail about ADS performance in focused ADS integration challenge scenarios than USDOT has openly collected to date.

Second, the demonstration and various activities programmed around it would educate South Carolinians on the benefits of ADS technology and inform statewide policymaking. To facilitate awareness of ADS technology and its benefits, CA4I will form an ADS Regulatory Leadership Advisory Council to hold biennial briefings on ADS benefits from research leaders. Other programming around the demonstration will educate citizens of Greenville County and other stakeholders in the state and regionally.

Finally, the project would accelerate Clemson's development of its own ADS talent pipeline. The past decade has illustrated the critical role of leading engineering schools in supporting the evolution of American global leadership in ADS development. However, for the United States to maintain its advantage in this crucial technology, it needs to expand educational opportunities for the next generation of ADS developers. Clemson's International Center for Automotive Research (CU-ICAR) is already a world leader in automotive engineering, and this project would accelerate the University's growth in automated and connected vehicle systems engineering.

B. ADDRESSING MARKET FAILURE AND OTHER COMPELLING PUBLIC NEEDS

In assembling this grant proposal, the Clemson team engaged several ADS technology integrators and other relevant suppliers to scope potential development pathways. However, the team found that many of these vendors either restricted data collection and reporting or imposed excessively stringent operational design domain (ODD) requirements. While this restrictive approach is understandable both from a liability and a proprietary perspective, it also has the effect of limiting market entrants and public examination of ADS safety issues by research institutions.

While Clemson University has the technical resources and capabilities to build and test ADS platforms on its own, to save cost and time, it has successfully identified willing industry partners that can help accelerate some aspects of automation, including hardware and software integration, to accelerate progress to the demonstration phase. The team has detailed its pathway to doing so in this application's technical approach. Nonetheless, to accelerate American development of ADS technology for both public and private sector stakeholders, Clemson would open its program to public audiences so future developers could benefit from the progress it makes.

C. ECONOMIC VITALITY

In addition to the aforementioned ADS talent pipeline development, the Clemson ADS project would promote economic vitality through support of domestic manufacturing industries and local workforce development in the Greenville region. All vehicles, ADS equipment, and infrastructure will be manufactured in the United States and compliant with the Buy American Act and other domestic vehicle preferences. Furthermore, Clemson and the Carolinas Alliance 4 Innovation (CA4I) will support local workforce development initiatives throughout the project period and beyond. This will include, but is not limited to, safety driver training, educational programming for local middle and high school students, and continuous engagement with the numerous automotive manufacturers and suppliers based in South Carolina.

D. COMPLEXITY OF TECHNOLOGY

Given the developmental state of current ADS technology, and the existing legal opinion at the state level, the Clemson team deemed SAE L3 automation to be the most viable target for safe demonstration on public roads. Regarding which technology solutions to implement, the team has identified two automation software/hardware platform options that satisfy DOT's goals for the project to provide as much open access to safety-related ADS L3 demonstration data as possible. These options are described in Section 5A.1 of this proposal along with our approach to updating the selected transit vehicle platforms with automation capability. The project will provide a comparison between these two options by deploying one on each of the two transit vehicles. Along with our identified industry partners, and Clemson's focused experience and resources in automotive systems, the team will be able to make any additional modifications on software and hardware that will enable evaluations of the driving policies for the ADS on the identified domains, as proposed in the rest of the technical approach section.

E. DIVERSITY OF PROJECTS

The proposed demonstration would serve a substantially different use case than other public sector ADS projects to date: on-demand transit vans in a low-density suburban environment. Most projects have focused on low-speed automated shuttles in dense urban areas, particularly around tourist districts, and have often neglected less-dense areas due to the challenges associated with covering greater distances at higher speeds. However, the project team sees a clear need for more ADS demonstrations in these land use scenarios to evaluate the technology's performance and increase its public acceptance.

Lower-density cities that struggle to justify standard fixed-route transit service with 35- or 40-foot buses have been experimenting with "microtransit" pilot programs using light commercial vehicles in on-demand or variable-route service. Examples include pilots in Arlington, Texas (Via), Snellville, Georgia (Transloc), and Sacramento, California (Transloc). Few have integrated this type of demand-responsive transit service with automation and given the significant cost reductions achieved by reducing the need for driver labor that could make these services more viable, this project would serve a clearly demonstrated research need. Though this project only seeks to prove L3 automation, L4/5 would be the eventual objective to enable that service.

F. TRANSPORTATION-CHALLENGED POPULATIONS

Greenville's transportation-challenged populations include seniors, adolescents, and others with age or physical limitations that prevent them from driving, and low-income individuals who cannot afford to own vehicles. Greenville County's Greenlink transit system operates primarily in a hub-and-spoke capacity, connecting area residents to downtown Greenville. A single route passes through Mauldin, providing little connectivity between destinations in that community.

The Greenville Chamber of Commerce's Workforce Data Collaborative (WDC) identified the Mauldin area as qualified for an ADS demonstration. In 2018, the WDC collected and analyzed data to examine barriers to workforce participation and availability and opportunities to enhance participation. One of the four major barriers to employment identified was transportation, and the study aimed to inform efforts to remove barriers to workforce availability & participation. 63% of workers surveyed said they "definitely or probably" would utilize a circulator bus in the City of Mauldin, and 80% of employers said they "definitely or probably" would support implementing a circulator bus route that serviced locations around the City of Mauldin. An automated on-demand service would offer more cost-effective transportation for residents travelling within Mauldin. In this project, the third demonstration scenario would engage passengers in Mauldin to introduce them to automated transit van service.

G. PROTOTYPES

After the drive by wire (DBW) retrofit, our two transit vehicles will be safe to operate on public roads, though technically still considered prototypes. The DBW can be deactivated by a human driver through various means as described in the technical approach (5A.1). The automation capabilities will be implemented as prototype systems that will be enabled by the team to allow safe demonstrations. We describe a phased approach to evaluate safe driving policies for the ADS via VIL testing, controlled-traffic in a closed test track and finally on public roads. In Section 5Bi), we describe our assessment of compliance with FMVSS for the vehicles and how we plan to disclose our functional safety analysis on the capabilities we will add.

4. REQUIREMENTS

A. RESEARCH AND DEVELOPMENT OF ADS TECHNOLOGY

This project will target research, development and demonstration of SAE L3[9] vehicles on public roads and in a closed test track. As detailed in the Section 5A.1, we will integrate hardware and software on the two vehicles to enable sustained automation of the dynamic driving task

(DDT), within operational design domains (ODD) defined by the selected demonstration sites. By the dynamic driving task, we mean all **tactical and operational** functions required to operate a vehicle on the road; namely, lateral and longitudinal vehicle motion control, monitoring of the driving scene via perception/OEDR, decision-making and motion planning, and visual communication with other road users. Because L3 automation still requires an attentive driver behind the wheel, a trained safety driver will remain in the driver's seat at all times during the on-road demonstrations, ready to take control of the vehicle when prompted to do so. Our ADS will be enabled to determine when it has exceeded its *ODD limitations, or other relevant ADS failures occur,* and will prompt the safety driver to intervene. In our research and development process, the safety driver will have the ability to disengage the ADS for any reason; a feature that allows our researchers to experiment as we refine and study different driving policies.

The specific R&D work areas include: 1) Evaluation of requirements for safe driving policies for ADS operating in public traffic, 2) Evaluation of different automation software stacks currently available for perception, decision making (driving policy), motion planning and control implemented on two similar vehicles, 3) Evaluation of several (C-)V2X safety applications by deploying a prototype heterogenous network (HetNet) on the demonstration sites, and 4) Use of a novel traffic observation system to study the behavioral traffic interactions involving ADS.

B. PHYSICAL DEMONSTRATION

All phases of the project involve demonstrating ADS vehicles in physical environments, beginning on a test track in Greenville, and then moving to public roads. The test track and on-road demonstrations will constitute most of the planned project work in years 2-4. Even the use of vehicle-in-the-loop (VIL) simulation will incorporate physical ADS vehicle operation on the closed test track when interacting with simulated virtual traffic.

C. GATHERING AND SHARING OF DATA

We will share extensive and appropriately collated data with USDOT in near real-time through clearly established sharing mechanisms. The team will also report findings to USDOT and the public through various channels. Specific data collection and sharing procedures are outlined in Section 2(B) – above.

A data storage system will be set up and maintained by Clemson including a project website with public access protocols that allows wide sharing of the data with other developers and researchers. Milestone demonstration events will be live-streamed to DOT and the public. Web access will also include visualization tools to promote further analysis of the data by other researchers and for use by educators. The stored data will be accessible to the US DOT and the public for a minimum of 5 years after the project ends. We do not anticipate data sharing limitations due to proprietary concerns on the most important safety relevant data such as OEDR outputs, actuation signals and trajectories. We will also take steps to protect personally identifiable information in the observation data (safety driver, other traffic participants, license plates, etc.). Data storage and management costs are included in the project budget. Further discussions on the data management, access and sharing protocols are given in Part 3-Draft Data Management Plan. Clemson University *will negotiate and sign* a mutually agreeable data sharing agreement with USDOT upon award for at least the defined minimum period.

D. USER INTERFACES

Our implementation of a human-machine interface (HMI, Section 5A1) will foster interaction between passengers with varied abilities and the ADS. The HMI includes speech and gesture recognition functions, as well as heads-up displays and text interpreters for inputting/displaying destinations or navigation information. It also allows users to receive intervention commands as voice and displayed alerts from the ADS.

E. SCALABILITY AND OUTREACH

The three on-road demonstration sites selected are representative of typical medium-density suburban road environments for many mid-size American metros. Therefore, the ADS solutions we will demonstrate can be rapidly scaled and duplicated for further evaluation and deployment throughout the country, allowing for some regional differences such as seasonal weather conditions and topography. In addition, we include the following outreach tasks to promote the demonstration and assist with scaling the findings nationwide:

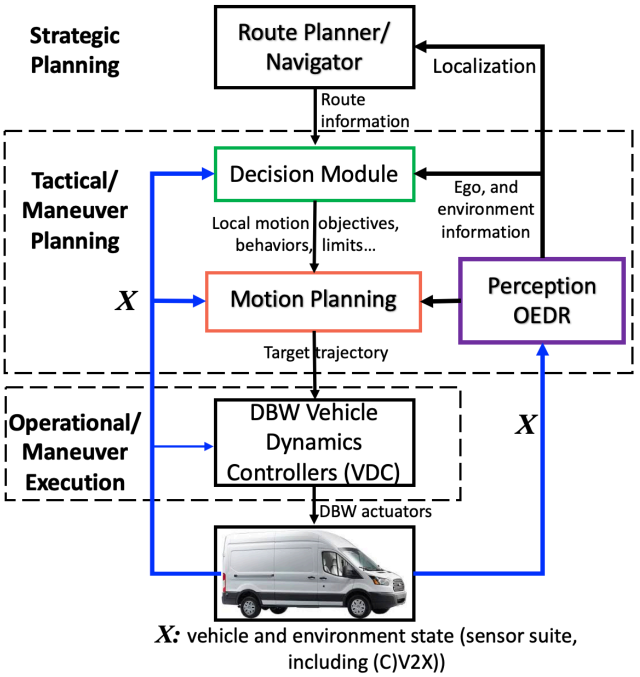
- Build a dedicated website that live streams milestone demonstration events and provides access to replay of the demonstration data using virtualization apps, along with descriptive blog posts by the team.
- Conduct outreach to the ADS industry using the resources of community partners, including CA4I, to attract demonstration participants locally, share expertise, and use generated data.
- Work with other demonstration sites to exchange lessons learned with other jurisdictions to promote knowledge transfer and technical exchange.
- Commit to host two symposia (conferences) accompanied by demo days focused on ADS in the premises of CU-ICAR and ITIC in collaboration with SAE (Support letter included). CU-ICAR has already hosted such an event in 2018. The goal of this specific demonstration will be to engage standards development committees within SAE.

5. APPROACH

A. TECHNICAL APPROACH

To facilitate the discussion of our technical approach, we will first describe our terminology. Figure 1 presents a schematic of the task hierarchy and functional modules needed to execute the dynamic driving task (DDT) with ADS. This hierarchical framework is modeled after that of a human driver; adaptations of the framework for autonomous vehicle guidance is given by Clemson researchers[10] and others. At the top is the strategic level involved with planning for routes, and in the middle is the tactical level involved with short-term decisions (seconds) using outputs of the perception (OEDR) module and knowledge of the current state of the ego-vehicle. The perception/OEDR module undertakes object and event detection, situation classification, *object tracking and prediction, and risk assessment*. The outputs of the decision module can be viewed as definitions of the local motion objectives or behaviors (e.g. turn left, brake, change lane etc.). The objectives will be met via tactical trajectory planning, followed by the operational execution of the planned/target trajectory via the low-level vehicle dynamics controllers acting on the steering, acceleration and brake actuators. In our project, these will be collectively called DBW (drive-by-wire) actuators. The decision and motion planning modules are very closely constrained by OEDR outputs.

In this proposed demonstration project, we focus mainly on aspects of this hierarchy relevant to the goal of the proposed demonstrations, i.e., the design of the tactical level modules, where the on-board *driving policy* resides for the ADS, and, in our view, constitutes the level of the DDT hierarchy that **poses significant challenges for the safe integration ADS on public roads**. This is not to understate the importance of more developments in the other modules, rather it is to assert that even as other modules continue to be refined (e.g. sensing technologies, motion planning and control algorithms), having the correct driving policy on-board remains critically important for the ADS obeying the 'rules of the road' as expected by other road users (human-driven vehicles, pedestrians). This has a direct implication for the kinds of standards and regulations that should be developed.



X: vehicle and environment state (sensor suite, including (C)V2X))

Figure 1. DDT task hierarchy and functional modules in ADS

In general, the **decision module** is implemented as a finite state machine (FSM) which contains the driving policies for the OEDR determined scenario at hand (to stop, to overtake, to change a lane, or observe speed limits, etc.). For each driving scenario, various conditions (rules) will be incorporated in the FSM, as collections of FSMs, that determine the desired local behavior of the vehicle. A simple example FSM is the following: if the ADS vehicle is approaching a vehicle in front and predicts a time to collision (headway) that is below a threshold, then its desired local behavior should be to change a lane, if an adjacent one is allowable/open with enough gap, or to slow down with a deceleration rate that remains safe despite the worst case/sudden deceleration by the leading vehicle. There are several parameters in this FSM such as the threshold, gap evaluation, deceleration rate, etc., that make up the details of the driving policies that will be varied in the demonstrations described in Section 5A.2. Good decisions facilitate the tasks of subsequent safe and optimal **motion planning** computations (which further enforce obstacle avoidance with dynamic re-planning). Several established algorithms exist to this end (way-point tracking, RRT, hybrid A*, etc.) including some of our own implementations that blend the decision and motion planning tasks in physics-based predictive control framework. In this project, we will deploy and compare two options of technology stacks for the tactical modules that leverage open-source tools being developed and adopted by industry as we describe below.

A.1 VEHICLE, HARDWARE AND SOFTWARE PLATFORM

Vehicle Platform and DBW Adaptation: The automotive engineering graduate program at CU-ICAR has extensive experience with building vehicles from the ground up for different use cases through Clemson's flagship Deep Orange Projects. Deep Orange 8 and 10 focused on autonomous vehicle concepts. Furthermore, three Clemson faculty on our team currently operate two vehicles (a Nissan Leaf and a Mazda CX7) retrofitted for automation by the team with in-house designed robotic systems[11] including DSRC V2X connectivity and are being used in another federally funded (US-DOE) CAV project on the ITIC test track. However, for this proposal, to enable demonstrations on public-roads with street-ready vehicles, we propose to adopt a commercial-grade retrofitting solution of Ford Transit passenger vans. This platform/chassis is *interoperable* across fleets for delivery and transit (shuttle) applications in urban and suburban environments. Clemson will purchase two of these vehicles and have them retrofitted for drive-by-wire (DBW) functionality by our partner company New Eagle, a control systems integration company based in Ann Arbor, MI (Letter of commitment included). Participation in this project is also an opportunity for New Eagle, which already supplies DBW kits for popular retrofitted platforms such as the Chrysler Pacifica, to develop new kits that can be used for automation of delivery and transit vehicles.

DBW retrofitting allows automation systems access to the steering, accelerator/braking and shifting functionalities on a production vehicle. Figure 2 shows a schematic of the New Eagle DBW architecture with interface to Robot Operating System (ROS) automation middleware as an example. The DBW retrofitting involves installing a DBW vehicle control unit (VCU) which issues commands to and receives feedback from the shifting, steering and brake/throttle via the vehicle's CAN bus. The VCU communicates with ROS DBW nodes interfacing with the higher-level motion planning and perception functionalities. Several interfacing options are available for each of the DBW actuators, in terms of physical control signals (command/feedback): steering angle/torque, pedal position or speed with acceleration/jerk limits. Of particular importance for our research-oriented demonstrations are the facilities for <u>disengagement of automation</u> (by a safety driver), for which several signals will be monitored: driver turning a steering wheel (torque sense) or hitting any of the accelerator/brake pedals or adjusting shifting, a E-stop, and heartbeat counter to ensure that the higher-level automation is active. These disengagement conditions are in addition to any call to exit from autonomous mode, as in L3 ADS's fallback request to intervene issued to the safety driver when it detects malfunction or is about to exit its ODD.

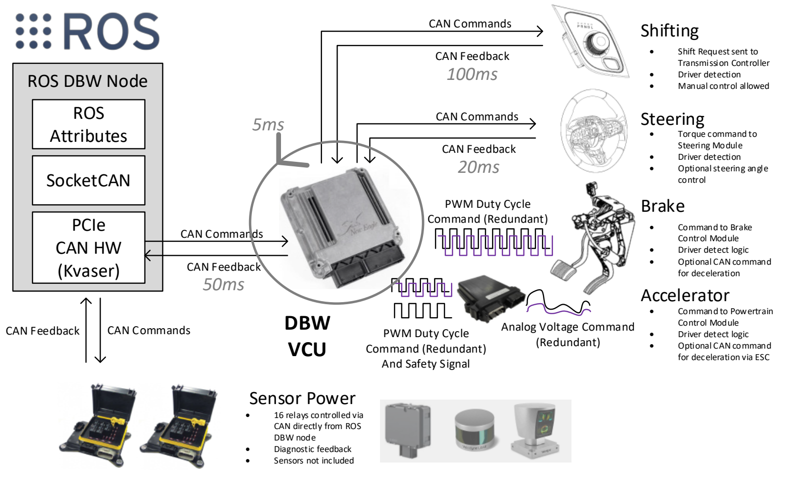


Figure 2 Architecture of DBW system interface by new eagle

<u>Automation Integration:</u> Following installations of the DBW, the Clemson team will proceed with the systems integration work for the rest of the software and hardware modules that will enable L3 automation.

Selection of sensors / perception architecture: In order to satisfy the perception requirements for autonomous navigation imposed by the proposed demonstration scenarios that include urban and suburban driving with stops to the right side of the road, we have performed a benchmark study of sensor positioning for existing autonomous prototype vehicles such as Waymo, Ford, Uber, Tesla S and Aptiv, as well as our own Deep Orange concept vehicles. We will deploy different sensor sets on the two vehicles (depending on the software platform capabilities below) each consisting of suites of radars, lidars, RGB and thermal cameras, real-time kinematic (RTK)-GPS, Inertial Measurement Unit (IMU), ultrasonic sensors and odometry sensors. Radar will provide a long- and mid- range perception of surroundings and LIDAR will provide a finer high-resolution 3D perception of surrounding objects in short- and mid- ranges. Ultrasound further complements short-range coverage. Cameras, along with thermal cameras, are used to detect and recognize surrounding objects such as vehicles, pedestrians, traffic lights, road signage, lane markers, etc. RTK-GPS and IMU will provide precise location (centimeter level) and orientation of the vehicle in real time. These sensors overlap in perception, providing redundancy for robustness and enabling fusion to generate more accurate, reliable, and complete sensing and surroundings. The placement of the sensors will be decided considering a motion model of the vehicle to eliminate blind spots for the ADS in all motion scenarios. (C)V2X connectivity augments safety applications, such as collision avoidance.

Software Stack Hardware and Operating System	Perception/ OEDR Processing Applications	Decision making and motion planning	Comments
Autoware Stack Hardware: Multi-core CPUs OS: ROS, Linux, Ubuntu	-Scan matching of HD Maps and 3D lidar (SLAM) or fuse RTK-GPS+IMU+lidar for localization - Established machine vision, sensor fusion, and deep learning algorithms for detection of objects and traffic lights and signs, and prediction of object motion	Finite state machine (FSM) for decision (rule-based); and trajectory (way-point) planners such as hybrid-state A*, and custom trajectory planners	Pro: OPEN and flexible and can be expanded as desired Con: Open tools need further refinement for specific use cases
NVIDIA Drive OS, Drive AV, Drive IX (HMI) Hardware: Drive AGX Xavier, GPU+CPU	Deep Neural Networks (DNN) for sensor fusion, localization, detection, object classification, collision-free space detection and prediction	New Safety Force Field(SFF); Physics-based frame by frame decision and motion planning module; Openly available March 2019. Similar to RSS from Intel/Mobileye.	Pro: fully developed perception stack, ISO26262 compliant processes Con: DNNs are proprietary, although the OEDR outputs and control are open (most relevant to safety analysis)

Table 2 Two options of automation software stack and hardware

Selection of Automation Software Stack: Table 1 shows two automation software and hardware options that we will deploy on the two vehicles (one option on each), including brief comments on the pros and cons of each that we have identified. For the Autoware option, we will collaborate with Autonomous Stuff (AS), a major autonomy integrator and provider of customized Autoware implementations. We included the NVIDIA DRIVE option on the 2nd vehicle, because the approach and tool has been widely adopted by major OEMS and Tier I suppliers for both ADAS (SAE L2) and automation development. Furthermore, NVIDIA recently made their physics-based Safety Force Field (SFF) approach to decision making and motion planning/control openly available. We believe implementing both options will be useful for benchmarking purposes for DOT and others. We also plan to leverage Clemson's existing collaboration with NVIDIA in the Deep Orange 10 project. The project team will compare these two options installed on the vehicles operating on similar environments. After sensor and initial software installation and HD mapping of the demonstration areas in Greenville by AS, the Clemson team plans to expand the capabilities of either or both vehicles by adding additional sensors as needed, updating OEDR functionalities, and altering the parameters of the decision making and motion planning modules as part of its demonstration work. The Clemson team includes several faculty members who actively work in these technical areas including Drs. Ayalew, Jia, Pisu, McClendon, Vahidi and Li.

ODD Safety Diagnostics: While traditional functional safety approaches include many aspects of fault management, they do not necessarily deal with requirements gaps and ensuring safety when the system encounters edge cases. In particular, the ADS must be capable of handling system limitations, system faults, and fault responses. System limitations include current capabilities of sensors and actuators, detecting and handling vehicle excursion outside the ODD, desired availability despite fault states including graceful degradation, degradation due to payload changes, variations based on functional modes, and in case of V2X, incompleteness, corruption, incorrectness or unavailability of external information. System faults include perception failure, transient and permanent faults in classification and pose of objects, planning failures, vehicle equipment operation faults such as engine stall, brake failure, and steering failure, operational degradation of sensors and actuators including temporary conditions such as those due to dirt, dust, heat, water, and incorrect map data or training data incompleteness.

Our approach aims to ensure safe operation of the SAE L3 vehicle through autonomous action at run-time. This applies to all thinkable situations during normal operation, but particularly to all situations in which system boundaries may be crossed or have been crossed, and therefore maintenance of operation is no longer possible. Two primary tasks of the proposed safety approach are: 1) permanent monitoring of ODD boundaries at runtime during normal operation, and 2) provision of action plans for degraded operation mode or transfer control to the driver (fallback layer). This approach seeks to produce a runtime representation of the domain in which the ADS can currently safely operate regardless of the functional degradation. The objective is to create a map between degraded system functionality and ODD constraints. This requires an ODD definition that can be monitored at runtime and on predefined subsystem degraded operation modes (DOM). A benefit of this approach is that it requires only mapping DOM in a subsystem to specific elements of the ODD. This requires the subsystems to be aware of ODD elements that are relevant to their operations and adjust accordingly. For example, a trajectory planner would need to know the ODD elements that represents the subject vehicle's maximum acceleration/deceleration capability. We will use an ODD ontology provided by the "Operational World Model"[12] which consists of six categories: 1) Road structure, such as road geometry, traffic lights, signage, etc.; 2) Road Users, such as vehicles (cars, buses, bicycles, motorcycles), humans, and combinations of them; 3) Animals, such as supervised and unsupervised animals; 4) Obstacles; 5) Environmental conditions, such as atmospheric, lighting, road surface; 6) Subject Vehicle Behavior, including functionality and limits of the vehicle (turning radii, speed limits).

The proposed health monitoring architecture for enabling this safety approach consists of a perception impairment monitor, a supervisory health monitor, and ODD monitor and an HMI interface for driver intervention requests, connected as depicted in Figure 3. The perception impairment monitor is responsible for detecting sensors and perception software malfunctions (both temporary or permanent), sensor impairments associated to confounding factors, e.g. camera obstruction and other environmental conditions affecting the perception sensors and reports the corresponding DOM to the supervisor health monitor. The supervisor health monitor is responsible for maintaining information about the overall system health as a combination of all the DOMs of the various sub-systems and contains mappings of DOMs to ODD constraints for the various subsystems. For example, if a right-side facing vehicle detection system fails, the map would constrain the set of maneuvers to exclude left turns at intersections. It also communicates with the ODD monitor, providing information on current ODD constraints, from which it receives notifications of upcoming or immediate constraints violation, triggering an immediate driver intervention through the HMI interface (described below). The ODD monitor uses the information received from the supervisor health monitor to determine if the ADS has violated the ODD constraints or if an unavoidable upcoming ODD constraints violation is detected.

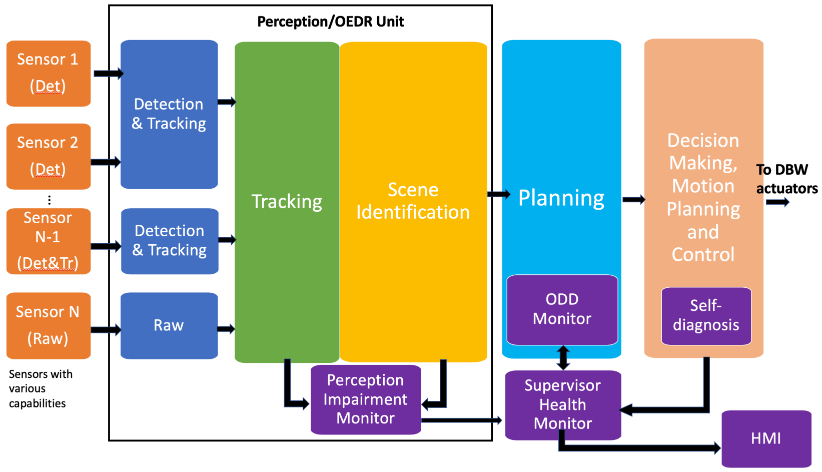


Figure 3 Proposed ODD health monitoring architecture

In line with the requirements for SAE L3 autonomy, we assume that the safety driver is receptive to ADS-issued requests to intervene and to performance-relevant system failures and will respond appropriately. We will assure that the DBW system, and the hardware running the functional modules executing the DDT are ISO 26262 compliant and, therefore, have redundancies with high ASIL and self-diagnosing capabilities (see DBW discussion earlier).

Human Machine Interface (HMI): As part of the ADS software stack for SAE Level 3 vehicles, an HMI is required. This HMI interacts with passengers inside the vehicle by taking their navigation instructions, such as their destination address. For the proposed work in this demonstration, navigation instructions can be given by the user in the form of speech commands or typed using a virtual keyboard appearing on the heads-up display (HUD) of the vehicle. En route to the destination, the HMI provides feedback regarding anticipated time to destination or re-routing information, the state of the ADS, or if the vehicle has stopped because pedestrians or stop signs were detected. This feedback is provided to passengers as text on the HUD as well as through a voice interface where the notification is spoken to the passengers and the safety driver. Given the L3 ODD diagnostics described above, the HMI is also tasked with alerting safety drivers with timely requests to intervene.

A.2 DEMONSTRATION WORK PLAN

Traffic Domain Selection and Demonstration Contexts

After careful consideration of use cases, we selected the following three traffic domains for on-road demonstrations: (1) light traffic environment around the CU-ICAR neighborhood, (2) a section of major arterial spur (US-276) between downtown Greenville, SC and Mauldin, SC; and (3) a loop around Mauldin town-center serving a senior center. These traffic domains are of increasing complexity to allow us to pursue continuous refinements in our demonstrations. Each traffic domain features several scenarios to study challenging decision areas for ADS vehicles interacting with other road users: left turns onto two-lane roads, roundabouts, signalized and unsignalized intersections, changing traffic patterns with freeway (I-85) entry and exits, merging, changing speed limits, etc.

Instead of approaching ADS safety verification that emphasizes exposure, i.e., driving for several millions of miles, as developers with more financial resources are doing, etc., we take a scenario-intensive approach that allows us to focus demonstration work on *the most challenging aspects of ADS integration* into public road traffic. Admittedly, a complete enumeration of high-risk scenarios that an ADS could face on public roads is challenging, as these could theoretically be infinite. To manage cost and time, and *still generate valuable data that is relevant for rule-making*, we have devised the demonstration work plan depicted in Figure 4.

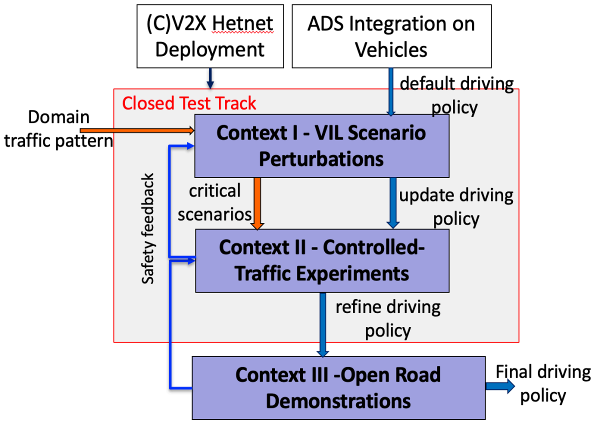


Figure 4. Overview of demonstration work flow

The demonstration work on each traffic domain begins with analysis of the traffic pattern using the external traffic observer system we describe in Section 5A.5. The traffic pattern analysis would focus on sections of the identified roadways where the ADS is expected to interact with other road users with elevated safety risks. We expect many of these scenarios to be similar to those identified in the *typology of the pre-crash scenarios* by NHTSA's analysis of the General Estimates System crash database[13]. Then, we proceed to the VIL scenario perturbations work on the test track, where we will primarily recreate these scenarios on the test track by directly mapping the identified roadway areas and traffic situations in a traffic simulator or by altering the perception outputs (e.g. occlusions). In the VIL simulations (detailed description in Section 5A.3), the physical ADS vehicles operating on the closed-test track will interact with simulated traffic representing the domain traffic under study. By perturbations we mean alterations and randomizations of the observed scenarios: 1) actions of other road users, 2) the decisions of the ADS (*the parameters and semantics of its tactical driving policy*) and 3) perception and traffic variances which can be easily manipulated in the VIL setting. We will conduct design of experiments (DoF) on these variables. We will also include rare-event emulations for accelerated testing (see Section 5A.3). The VIL approach uniquely allows us to test several combinations with minimal safety risk to researchers or the public. We expect the output of the VIL experiments will identify critical scenarios for which refinements of the driving policies of the ADS are warranted before proceeding to the next phase of controlled-traffic experiments.

The controlled-traffic experiments involve aware participants (other vehicles, pedestrians, etc., with appropriate training and human subject IRB approvals) who will interact with the ADS vehicles in controlled experiments on the closed test track. Participants will be trained and instructed how to behave (speed, direction and timing, for driving, walking, etc.). These experiments pose some safety risk to participants and admittedly *introduce bias* from the experimental safety measures we will put in place to minimize this risk. For example, the ADS vehicles will not be allowed to break safety envelopes (will enlarge time-to-collision thresholds), which may otherwise happen on uncontrolled open road experiments. Still the experiments could give valuable information by accounting for this expected bias.

Finally, after all necessary refinements of the driving policies have been incorporated (tuning of, as appropriate, the decision making, motion planning and OEDR modules of the ADS), have been incorporated the demonstrations will be moved to the on-road setting in traffic domains (1), (2) or (3) under consideration.

Prototypical ADS Integration Scenario Demonstrations: Using the three settings/contexts in Figure 4, we will also explicitly consider some prototypical scenarios of increasing complexity that pose challenges for integration of ADS within the current on-road traffic: a): Mixed single lane traffic involving human-driven and ADS vehicles (including platooning, using the (C)V2X infrastructure described in Section 5A.4; b) Changing lanes; c) Crossing and turning at intersections; d) Merging and exiting at roundabouts and ramps; e) Traffic object variability (e.g., pedestrians, motorcycles, heavy trucks); f) Emergency events (e.g., incidents, emergency vehicles); g) Variable driving conditions (e.g., weather, road condition, density).

Automated Longitudinal Driving Policies. We seek to establish regulations for safe integration of ADS in mixed single-lane traffic as well as in platoons (scenario a). We propose to adopt safety metrics mentioned earlier as criteria: crashes, near misses, rapid acceleration/deceleration, time to collision, and safety envelope violations. In addition to safety, we also will evaluate traffic efficiency because safety regulations may also affect traffic flow. For instance, large spacing may result in better safety at the cost of poor roadway utilization. We will conduct statistical analysis via a design of experiments where we vary policy parameters of common longitudinal automated driving policies (e.g., car following control, adaptive cruise control, cooperative adaptive cruise control) under different settings (e.g. domain speed limits, traffic density), to derive possible ADS regulations for spacing (time headways, or distance at speed), and acceleration/deceleration limits to achieve reduced safety risk without exacerbating traffic flow.

Automated Lateral Driving Policies. We will use scenarios b), c) and d) above to study possible driving policies leading to regulations in ego-vehicle yaw rate and lateral acceleration profiles and limits during turning maneuvers; lane change conditions and trajectory requirements; conditions that may lead to disengagements; conditions and trajectory requirements for left/right/U turns; conditions for negotiating right of way conflicts when entering/existing roundabouts and freeway entry/exit ramps. We will conduct demonstrations via a design of experiments where we vary the policy parameters of common lateral automated driving policies (e.g., lane keeping, lane change, take-over, intersection turns, and roundabout) under different settings (ego and traffic states).

With the longitudinal and lateral driving policy investigations, minimal performance requirements for the ADS sensor suite, telecommunications, and other infrastructure can also be established during these studies. This is especially straightforward in the VIL test track experiments, as perception and communication parameters are easy to manipulate in that setting without adding new sensors or infrastructure.

Automated Handling of Traffic Variances and Uncertainties. We will use scenarios e), f) and g) to study possible driving policies regarding ADS handling of different road users, incidents and construction zones on roadways, emergency vehicles; weather conditions such as different levels of rain and fog; lighting/visibility conditions such as day and night time; road conditions such as dry, wet and slippery grounds. Since these situations are generally hard to control for experiments on public roads and report statistically meaningful results from our restricted ODD, our approach will rely on our novel VIL setting to emulate and perturb some, but not all, of these situations. However, information about such situations that may be experienced during the on-road demonstrations will be recorded and reported to DOT. The expected outcome of these demonstrations will be to provide guidance for regulations on ADS vehicle behaviors (e.g., speed, distance, acceleration, braking) when facing the listed traffic variances and uncertainties.

Safety Driver Training. In this project, since characterizations of disengagements will form part of the ADS safety evaluation, it is important to have consistent protocols for the safety drivers to follow. This is to minimize variability and uncertainty associated with the different risk thresholds and intervention behaviors that human drivers exhibit. To this end, we will collaborate with SAE to offer ADS intervention training specific to our Level 3 vehicles to our safety drivers (primarily Clemson development engineers) and establish procedures for consistent intervention and reporting of experiences during the tests, particularly of events that necessitated the intervention. We will specifically follow the guidelines offered in SAEJ3018[14] on this topic. To limit distractions, we will minimize reporting workload to the safety drivers by including voice reporting of incidents from within the vehicle that will also be reported in real-time to the monitoring station and recorded for subsequent analysis.

A.3 DETAILS OF THE VIL-IN-THE LOOP (VIL) TEST BED

In the proposed VIL test bed, depicted in Figure 5, our experimental physical ADS vehicle operating on the test track will *interact* with simulated neighboring vehicles in a traffic microsimulation environment through wireless communication. Crashes can only happen in simulation, thereby providing a low-risk approach to refine ADS driving policies. When the goal is to evaluate robustness to perception errors, alterations can be done to OEDR module inputs and outputs on-board the ADS vehicle itself (This is one reason to include an open, editable, OEDR software stack on one of our vehicles (Table 1)). With VIL, critical and worst-case encounter scenarios that are statistically rare can be simulated to stress-test the ADS decision and motion planning modules.

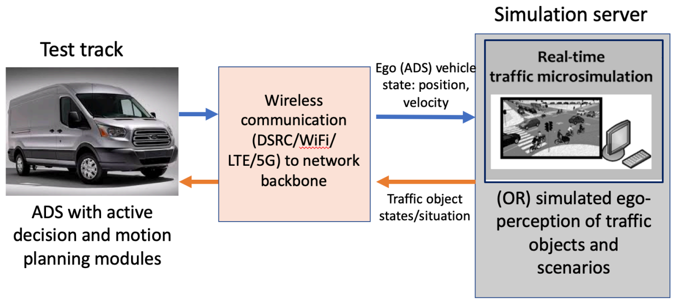


Figure 5 Vehicle-in-the Loop (VIL) simulation set up

This is a leap forward with respect to the current expensive and risky practice of ADS developers of Naturalistic-Field Operational Tests (N-FOT), which involves operating automated vehicles on public roads for hundreds of thousands of miles.

The Clemson team has demonstrated the feasibility of a VIL testbed in two different projects. In earlier work, a real Clemson-designed vehicle interacted with hundreds of simulated vehicles and all communicated to an intersection control server. Since 2017, three of the Clemson PIs have been leading a US Department of Energy project to demonstrate the energy impact of CAV technology in mixed-traffic scenarios. We have adopted PTV Vissim for traffic microsimulations and made substantial effort in custom coding our own ADS control (decision and motion planning) modules in Vissim. We have also successfully established a VIL testbed with our two automated vehicles, as mentioned earlier.

For this project, as the ADS automation functionality is added to vehicles in Year 1, we will concurrently create “scenarios-of-interest” for testing vehicles first in a microsimulation setting. We will continue to use PTV Vissim because its high-fidelity vehicle-to-vehicle interaction models have made the tool an industry standard. It also includes provisions for interactions with pedestrians at intersections. PTV Group offered substantial cost share to this project by committing to make the full VISSIM package available to us, in addition to engineering support, due to interest in the potential of this VIL approach for ADS development.

Rare Event Scenario Generation for Accelerated Testing: Beyond the experimental VIL scenario perturbations mentioned in Section 5A.2 that focused on traffic domains and prototypical scenarios, we will consider relatively rare events such as real-world crashes that may not necessarily be recorded during on-road demonstrations but are nevertheless possibilities. To this end, we will obtain police reports for crashes that happened in Greenville and recreate those scenarios in a VIL setup. In the past, and in simulating automated vehicle car following and lane changing, Clemson researchers have set parameters such as acceleration and deceleration levels of neighboring human-driven vehicles and their driver model parameters by sampling from empirical probability distributions. Going further, we will apply the concept of *importance sampling* from statistics for accelerated testing of automated vehicles. To significantly reduce the number of simulations for accelerated VIL testing, instead of drawing samples from entire distributions one could attempt to draw from tail ends (rare events) that result in severe crashes. However, this will result in higher rates of crashes from induced bias of sampling from tail ends. With importance sampling, one maps the results back to the original underlying distribution. As a result, one could re-create rare crash events with much fewer samples and less time.

A.4 DEMONSTRATIONS OF CONNECTIVTY APPLICATIONS FOR SAFETY AND MOBILITY

The South Carolina Connected Vehicle Testbed (SC-CVT): This is a standards-based Connected Vehicle (CV) testbed that has been deployed near Clemson’s main campus. The system consists of three Dedicated Short-Range Communications (DSRC) road side units (RSU) that offer continuous DSRC coverage along a 1.4-mile stretch on Perimeter Rd. We have also deployed a 4G LTE (Long Term Evolution) cellular network coverage that overlaps the DSRC coverage providing a wireless heterogenous network (HetNet) that we own and operate. Prior research on this test bed has explored the design and evaluation of several V2X (vehicle to everything) safety applications including Queue Warning and Platooning.

Safety and Mobility Applications with 5G-Extended HetNet. It is clear that there will be continual evolution in underlying wireless connectivity and communications options. Our proposal targets the next several years where V2X infrastructure will include DSRC, 5G C-V2X and even LTE. We would expect to see vehicles that support one or the other. We are in communication with multiple vendors planning to support OBU's that support both DSRC and 5G C-V2X. DSRC and 5G offer low latency to meet *ADS safety application* requirements (such as such as collision avoidance and pedestrian detection via short range V2V and/or V2P), whereas LTE offers wide area coverage for *mobility applications* (such as travel time reduction in mixed-traffic by minimizing stops at intersections). Our proposal leverages ongoing work on developing a framework to support V2X applications with advanced network capabilities by providing simple service abstractions which shield the application from having to deal with the complexity of managing access across different radio networks. Novel Radio Access Technology (RAT) selection and handover algorithms (middleware for 'smart infrastructure') will be developed that will select the best access point at a particular time for a particular *safety or mobility* application depending on the feasibility, accessibility, and data delivery requirements (i.e., temporal and spatial requirements). The HetNet framework will enable smooth handover between access points of the same technology (Horizontal Handover) as well as between access points of different technologies requiring a change in the data link layer (Vertical Handover). Different network-based criteria (i.e. delay, bandwidth) will be considered along with Quality of Service (QoS) requirements of the participating users/vehicles to make an informed decision for RAT selection and handover timing.

We plan on adding 5G's C-V2X capabilities to the infrastructure in the 2nd year of the project. We have identified vendors for this, one of which has provided a letter of support (ismartways). Since most of the components are portable, we intend to move the LTE+5G infrastructure to the ITIC test track, which already has DSRC capability and will be expanded for this project, and the on-road ADS demonstration sites in Greenville. Having multiple low-latency networks will also facilitate the transfer of vast amounts of data from the ADS nodes to edge nodes connected to the backbone network.

Connected vehicle safety and mobility applications work by enhancing *situation awareness* for a connected vehicle. To demonstrate these HetNet-supported applications, in the first year, we will conduct research and prototype demonstrations on applications that can take advantage of enhanced HetNet, via simulations and, to the extent possible, through physical testing with connected human-driven vehicles (no automation) on the current SC-CVT. Example demonstrations include algorithms for event dissemination and cooperative perception of traffic situations at both *route planning* timescales (several seconds, mobility application via LTE C-V2X) and *decision making and motion planning* timescales (safety application, such as collision avoidance with an otherwise occluded vehicle via DSRC V2V). When the ADS vehicle platforms become ready (years 2-4), the safety and mobility applications will be demonstrated on the ITIC test track and selected road domains in Greenville. DSRC OBUs/5G/LTE user equipment mounted on the ADS vehicles will interface with the automation software stack of the ADS vehicles. Since project funds purchase only two ADS equipped vehicles, we will involve our own experimental vehicles and connected human-driven vehicles to create a viable scale for V2V cooperation. Then, we can fuse the V2V communicated information (DSRC or 5G) on to the ADS software node relevant for the safety/mobility application. At algorithmic level, the computations involve decentralized data-association and track-to-track fusion of exchanged information at the participating CV nodes. We may also test a new family of V2V applications that allow connected ADS vehicles to coordinate their decisions and motion plans on multi-lane mixed-traffic, going beyond platooning. Clemson already has efforts underway to develop these applications. We will specifically compare performance trade-offs for these applications deployed via 5G and/or DSRC.

Cybersecurity Support

In order to provide the right level of protection for the CV network, a software-based security platform will be developed to protect connected AVs against cyber-attacks. Two layers of protection will be required: vehicle level and network level. At the vehicle level, we have developed several approaches for enabling resilient control of automated vehicles in cooperative platooning subjected to V2V network attack based on plug and play control design. These approaches provide real-time resiliency against denial of service attack and intermittent communication false data injection and replay attack[15]–[17]. These approaches aim to provide graceful degradation and enough time for the driver to take over control of the vehicle. Since some of these approaches are somewhat limited to a formation type of scenario (platooning), we propose to investigate a broader methodology enabling both V2V network attack detection and malicious vehicle behavior and higher scalability, which is independent on the particular traffic scenario or formation and appropriate for a SAE L3 ADS vehicle. The proposed idea consists of utilizing the information data sets from vehicle perception together with the local V2V shared data and local V2I shared data to run an on-board simulation to predict expected local vehicle behaviors. Provided all onboard sensors are working properly, the predicted surrounding vehicles behavior will be compared with actual behavior at the next time step. If the standard deviation of the error exceeds a given threshold, the vehicle controller will trigger a new state called “high assurance control” that will be solely relying on on-board data and provide graceful performance degradation. Under these conditions, if the ODD monitor (Figure 3) detects or predicts an unavoidable violation of the ODD boundaries, vehicle control will fall back to the driver.

At the network level, an intrusion detection mechanism will be developed to monitor the V2I communication traffic utilizing distributed edge devices executing recurrent neural network models trained on normal and malicious network communication. To train the models, we will use a set consisting of the following features: (a) individual DSRC and 5G connections, (b) content features within the connection, (c) traffic features computed over an appropriate time window. If an anomaly in the V2I communication is detected, the edge nodes will terminate the communication or broadcast a signal to all connected and automated vehicles in the area to switch to the high assurance control state.

A.5 EXTERNAL TRAFFIC OBSERVATION SYSTEM (*“GROUND TRUTH” MONITORING*)

Since a major goal of the project is to evaluate safety performance of the OEDR and decision modules of the ADS vehicles while interacting with other traffic participants, we propose to include a traffic environment monitoring system on our demonstration traffic domains and contexts. To this end, we propose to install “ground truth” traffic observer stations as shown in Figure 6 near areas of challenging interaction between the ADS vehicles and other road users. These observer stations will need to be able to detect, localize, classify, and track vehicles (with dimensions, and as bus, truck, van, etc.), pedestrians, and cyclists. Furthermore, they should accurately estimate the velocity vector and yaw rate of all road users to provide semantic scene understanding with subsequent processing.

To meet these requirements, we propose to deploy a vision-radar detection and fusion system for object detection and tracking that leverages AI-based image processing. Each observer station will include a high-definition 360° camera with an advanced computer vision algorithm to *classify and localize* objects, and an automotive grade radar that can robustly detect spatial locations and speeds of objects. These units will be installed on roadside poles near traffic domains of interest. The units will also include local data storage, which will be recovered for upload to the project data management system immediately after demonstration events for subsequent analysis by the team. For cost reasons, we plan to build and use about 3 such portable systems.

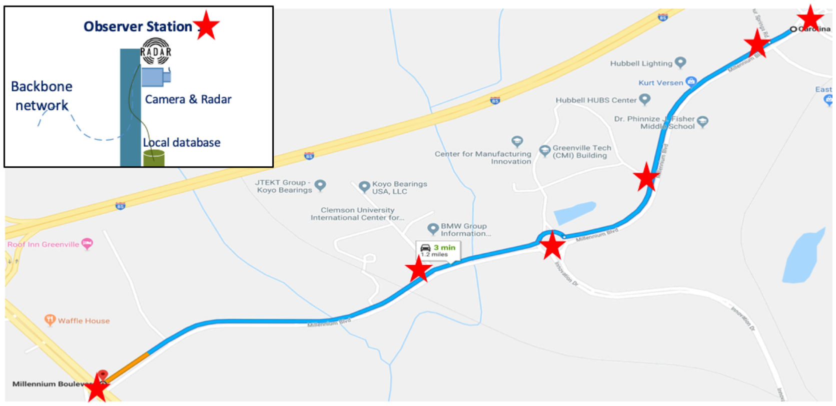


Figure 6 Traffic observer (monitoring) stations installed on traffic domain (1) in areas of ADS integration challenges; intersections, roundabouts, schools, etc.

Object Recognition, Tracking and Re-identification: We will apply a cutting-edge convolutional neural network classification model for this purpose, which has been shown to have top-5 detection accuracies, up to 97.749% [18] in the ImageNet Large Scale Visual Recognition Challenge [19]. Furthermore, a transfer learning technique can be applied to fine-tune the trained CNN model for higher accuracy. The CNN model is also able to detect and track pedestrians and cyclists reliably. We will also incorporate post processing steps from computer vision to estimate vehicle dimensions using additional information about road geometry and lane width. This task allows us to retrieve vehicle or object classes and their position and velocity vectors (magnitude and direction) in path aligned or global coordinates that we can report in a manner similar to the data reported in the NGSIM project of the FHWA[20].

Calibration of Observer Stations: We will procure high accuracy radars and run sensor fusion algorithms with the camera detection data. The observer/monitoring systems will be calibrated by running vehicles with independently verified localization and speed estimation systems (e.g. RTK-GPS+IMU equipped vehicles.

B. APPROACH TO ADDRESS LEGAL, REGULATORY, ENVIRONMENTAL OBSTACLES

i) FMVSS Compliance: A comprehensive review of Federal Motor Vehicle Safety Standards (FMVSS) for automated vehicles conducted by Volpe[21], as well as Clemson's evaluation of current practices in ADS development, found that as long as the vehicles do not significantly depart from conventional design, we face few barriers to FMVSS compliance. For this project, we will purchase commercially available vehicles and will always involve trained human safety drivers in our on-road demonstrations. We will also retain OEM-provided systems for meeting pre- and post-crash (crash-worthiness) safety requirements. The primary vehicle modifications proposed for the project target the integration of drive by wire (DBW) capabilities to the vehicles, which is a pre-condition for adding automation functionality. In adding DBW, the steering wheel assembly (FMVSS No. 203 and No. 204) and foot activate service brake design (FMVSS No.135) will be retained. The fail-safe condition for the added DBW interfaces will be the original OEM systems. Drive-by-wire systems and automation functionalities are not explicitly addressed by current FMVSS. In any case, we plan to follow rigorous ISO26262 risk assessment and functional safety analysis procedures with our adaptations and document those to DOT/NHTSA for voluntary self-assessment disclosure. We have recruited the support of KVA-functional safety experts to help with this aspect.

South Carolina has one active law specifically addressing ADS, HB 3289 (2017), which exempts platooning vehicles from safe following distance regulations on highways. Neither the state, nor any municipality designated as a demonstration site, prohibits or permits ADS operations by law. An August 6, 2015 opinion from South Carolina's Attorney General stated that any vehicle operated by ADS with a safety driver behind the wheel would be treated as any other human-operated vehicle under South Carolina motor vehicle laws. Since we will have safety drivers on board the vehicles on the public demonstration phases, the vehicles will be in compliance with state requirements. Nonetheless, we have sought and received commitments from SC DOT, SC DPS, the City of Greenville, and the City of Mauldin to operate these demonstration vehicles on their public rights of way. Should the state enact any further legislation regulating ADS, we will fully comply with it. The vehicles will be registered with the South Carolina DMV upon purchase and insured for operations both on the ITIC test track and the public roads designated as demonstration sites.

ii) Buy American and Domestic Vehicle Preferences: Our demonstration will not require an exemption under the Buy American Act, or an exemption under the terms of the NOFO Clause at Section F, Paragraph 2 entitled the BUY AMERICAN and DOMESTIC VEHICLE PREFERENCES. We plan to purchase two new Ford Transit passenger vans whose final assembly occurred in the US (Claycomo, MO) using direct Federal funds. Clemson will require – and the project manager CTE will verify – that all subrecipients and contractors comply with the domestic preference requirements at all tiers of subawards and contracts.

Clemson currently owns one 2013 Nissan Leaf and one 2009 Mazda CX7 that were retrofitted for automation to support other research work at Clemson and are being made available to the project at no cost. Since these vehicles were assembled outside the United States, they will not contribute to the project's proposed cost share.

C. COMMITMENT TO PROVIDE DATA AND PARTICPATE IN THE EVALUATION OF THE SAFETY OUTCOMES; MEASURES OF EFFECTIVENESS IN OTHER AREAS

The team is committed to providing full access to data collected during the demonstrations in as near real-time as possible. Recognizing that there are technical and cost limitations of data storage and network uplink capacities, some data will require compression and processing close to their source (on board the ADS vehicles, and off-board on the traffic observer systems). Nevertheless, Clemson aims to provide all raw data, as well as hierarchically processed sensor, actuation, on-board diagnostic data as described in Part 3-Draft Data Management Plan. The team is committed to participating in the evaluations of the safety outcomes of this proposed project with USDOT and all interested parties, with the goal to foster understanding of the possibilities and for further refinements the ADS.

The ADS technologies we will demonstrate could eventually scale with adoption in shuttle-style services to offer *increased mobility* for non-drivers, including elderly and disabled individuals. Though community outreach is programmed prior to the start of on-road demonstrations and throughout them, the project's last phase will more directly engage one demographic served by this use case. After sufficiently testing the ADS-enabled vehicles in the Mauldin ODD, we will collect rider data from seniors to assess the perceived safety of the ADS technology. CA4I will coordinate with the City of Mauldin and the Mauldin Senior Center to promote the ADS demonstration and recruit seniors to participate. CA4I will also create and facilitate surveys to capture feedback from riders on their perceptions of vehicle safety, comfort, and other measures. The team will report findings from these surveys to USDOT. CA4I will also convene workshops and symposiums to communicate findings from the demonstrations, to inform policymakers and planners on the challenges and potential benefits of deploying ADS.

D. APPROACH TO RISK IDENTIFICAITON, MITIGATION AND MANAGEMENT

CTE will guide the entire project by the control and risk management procedures detailed below. CTE's centralized management of the work program will enable team members to concentrate on exceeding project goals and ensure production of deliverables in a clear and well-coordinated manner. CTE's processes for ensuring the efficient accomplishment of these tasks include development of, and adherence to: 1) *Online Collaboration Tools, 2) Communications Plan* 3) *Reporting Plan (includes spending/progress versus budget tracking),* 3) *Schedule Control Plan.*

CTE provides strong and engaged oversight of project progress through the suite of management controls and tasks above. CTE's management method ensures quick recognition of any project risks that arise. Further, CTE's extensive experience managing projects allows for identification and development of clear mitigation strategies that address the needs of all stakeholders. The project approach includes identifying, documenting, and tracking issues. Issues are assigned to project team members for research, analysis, and resolution. Issues and related tasks are prioritized to ensure that project team members remain focused on the right activities at the right time. Critical issues that remain unresolved and that impact project timeline, scope, budget or resources are escalated to Clemson and DOT management, along with proposed solutions, for immediate attention. Throughout development of this project and proposal, the team identified and prepared for the following potential risks that are specific to this project.

1) *Route development*– The project team reviewed, visited, and selected the demonstration sites based on infrastructure, traffic flow, and human characteristics. However, unforeseen risks may present themselves that are associated with turning requirements, signaling, construction, etc. To address this, Clemson will accomplish a robust route planning activity, including riding the routes and modeling ADS functionality. Route adjustments may be made accordingly.

2) *Vehicle reliability and availability* – Given that the proposed vehicles will be new prototypes and may not be operational the entirety of the demonstration period, due to hardware or software challenges, necessary downtime could affect runtime and data collection. To address

this, Clemson's engineers will be trained and available to address component and system failure risks associated with the integrated ADS system. Most importantly, extensive validation testing has been included in the work scope prior to introduction into public service. Should any ADS system fail while in service, trained safety drivers will be available to take control of the vehicles.

3) *Accident or incident involving the demonstration vehicles*– Should an accident or on-board incident occur, whether or not it is due to the automated driving system and project vehicles, the team must be prepared to address liability concerns and risks. The team plans to accomplish this by keeping a safety driver on-board and behind the wheel at all times vehicles are in operation, securing an insurance policy, and working with local law enforcement to establish and prepare protocols in case of any incident.

E. APPROACH TO CONTRIBUTE AND MANAGE NON-FEDERAL RESOURCES

While cost share is not required with this NOFO, Clemson has secured and included several cost share commitments with this application. The University will contribute cost share in faculty release time for the project PI, and secure storage and garage work space (4000 sq ft) for the ADS vehicles. It will also cost share equipment usage time. The ITIC test track facility will contribute a cost share in reduced daily facility utilization rates, providing extended V2X coverage, installations of flexible roadway infrastructure for this project. New Eagle and Autonomous Stuff has provided cost share as discounts in their DBW development and automation integration services, respectively. Traffic simulation vendor PTV Group offered discounts on their software, and KVA will provide functional safety consulting and training time as cost share. CA4I has also provided in-kind match along with its subcontractors. In the long-term, Clemson intends to leverage this grant and the partnerships to generate more in-kind and direct research funding support from industry partners to ***sustain and expand research*** in the proposed Clemson-Center of Excellence in ADS (C-CEADS) beyond the focus of this project. We intend to adopt a successful Center model like that of an NSF- Engineering Research Center (ERC) or DOT's University Transportation Centers (UTC).

Clemson will require – and the project manager CTE will verify – that cost share committed to the project by named team members and other sources of contributions will be tracked appropriately and documented. CTE and CA4I will work with entities that have committed resources to ensure those entities fulfill their commitments. Clemson University requires all subrecipients to sign a subcontract on award which stipulates adherence to cost share commitments and award conditions.

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