Definitions, Verification, and Demonstration of Real-time Safety Metrics for Automated Driving Systems

A proposal submitted in response to:
Notice of Funding Opportunity (NOFO) Number 693JJ319NF00001
“Automated Driving System Demonstration Grants”

Issue Date: 12/21/2018
Application Due Date: 3/21/2019

By:
Raul G. Longoria, Ph.D., P.E. (PI)
Junmin Wang, Ph.D.
Kara Kockelman, Ph.D., P.E.
Christian Claudel, Ph.D.
Ufuk Topcu, Ph.D.

Cockrell School of Engineering
The University of Texas at Austin
Austin, TX

March 21, 2019

March 21, 2019

Federal Highway Administration
U.S Department of Transportation

Re: NOFO Number 693JJ319NF00001

Dear Review Committee:

On behalf of the project team formed here at the University of Texas at Austin, I am pleased to convey the attached proposal, titled:

Definitions, Verification, and Demonstration of Real-time Safety Metrics for Automated Driving Systems

in response to the above referenced NOFO.

We appreciate the opportunity to participate and to convey these proposed plans in support of advancing ways to ensure safe integration of Automated Driving Systems onto the nation's roadways.

Sincerely,

R G Longoria

Raul G. Longoria, Ph.D., P.E.
Professor
General Motors Foundation Centennial Teaching Fellowship in Mechanical Engineering
Walker Department of Mechanical Engineering
The University of Texas at Austin
r.longoria@mail.utexas.edu
(512) 471-0530

Summary Table	
Project Name/Title	Definitions, Verification, and Demonstration of Real-time Safety Metrics for Automated Driving Systems
Eligible Entity Applying to Receive Federal Funding (Prime Applicant's Legal Name and Address)	The University of Texas at Austin
Point of Contact (Name/Title; Email; Phone Number)	Raul G. Longoria, Professor r.longoria@mail.utexas.edu (512) 924-0530
Proposed Location (State(s) and Municipalities) for the Demonstration	Austin, Texas
Proposed Technologies for the Demonstration (briefly list)	L3 to L4 autonomy on Ford Fusion Real-time safety metrics
Proposed Duration of the Demonstration (period of performance)	9/19 – 8/23 (4 years)
Federal Funding Amount Requested	$3,011,686
Non-Federal Cost Share Amount Proposed, if applicable	$50,000
Total Project Cost (Federal Share + Non-Federal Cost Share, if applicable)	$3,061,686

Definitions, Verification, and Demonstration of Real-time Safety Metrics for Automated Driving Systems (UT-Austin)

1. EXECUTIVE SUMMARY

Introduction. Typical safety metrics, like NHTSA's 5-star crash-outcomes rating system, slope stability factors, crashes per mile driven, and distances between self-driving disengagements, are not sufficient for certifying safe operation of automated driving systems (ADS) on public roadways. Much more thoughtful, specific, and rigorous metrics are needed, to reflect the tremendous variety in roadway and intersection design "domains", traffic and weather conditions, real-time vehicle status, ADS technology characteristics and capabilities, and other evolving factors. The challenge in arriving at a solution to this complex problem is compounded by the highly diverse and often proprietary solutions currently being proposed by manufacturers and related companies. The lack of suitable metrics makes it difficult to evaluate a given ADS platform, especially across a range of different operational design domains (ODDs) (Czarnecki, 2018). Consequently, options for comparing different ADS and their relative safety or for guiding certification and end-user acquisition for use on public roadways remain limited and inadequate.

1a. Vision, Goals, and Objectives. This project will define and validate comprehensive and rigorous safety metrics and safe operational envelopes for emerging ADS that reflect vehicle hardware and software capabilities across a wide variety of meaningful ODDs. These metrics will inform *leading safety indicators* that can be used in real time (as a vehicle navigates any public route), while anticipating long-term crash savings from ADS deployments.

The project has four major goals: 1) establish a systematic approach for defining quantifiable and real-time ADS safety metrics and operational safety envelopes; 2) conduct controlled field testing to refine those definitions, data collection efforts, and data analysis, while demonstrating accuracies in real-time ADS safety envelopes; 3) implement full-scale demonstrations, data-sharing, and online monitoring and assessment methods; and 4) apply those safety metrics in new-vehicle (and new-vehicle-software) ADS classification and ratings systems.

This new "confident safety operating envelope" (CSOE) will reflect 1) real-time status and capability of ADS perception, decision-making, motion control, and actuation at the intra-vehicle level; and 2) the changing ODD, including driving behaviors and characteristics of surrounding vehicles at the extra-vehicle level. The safety envelope will dynamically update, enabling proactive communications with occupants and owners about ADS safety levels, including quantified confidence in whether the ADS system can sustain safe operation, especially during relatively extreme and hazardous driving scenarios. This information will be available in real-time for V2X communication, to ensure integration with higher-level safety systems, both local and network wide, enhancing safety of all travelers. The approach will rely on physics-based modeling, machine learning, agent-based simulations, virtual reality simulations, high-speed supercomputing, model verification and physical testing to establish a reliable framework for real-time safety self-assessments for ADS users and confidence of those regulating manufacture, sale, and use of vehicles within the U.S. Real-time monitoring of vehicles tested across a wide range of conditions will allow us to refine safety metrics for quantifying risk across common as well as extreme operations.

ADS demonstrations, for metric computation, testing and validation, will be conducted on controlled roadways, and then extended to approved roadways in the City of Austin. These on-road demonstrations - along with transparent and fundamentally sound methods for acquiring and interpreting data - will be used to evaluate scalability for use in mass-produced ADS.

More specifically, project objectives can be described as follows:

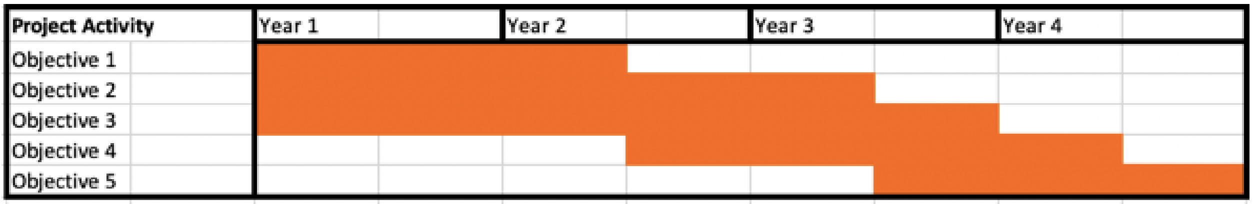
- **Objective 1:** Investigate, develop, and implement methods for defining reliable, accurate, and quantitative real-time ADS safety metrics.
- **Objective 2:** Develop and implement methods for generating real-time and dynamic safe ADS operational envelope based on key safety metrics.
- **Objective 3:** Develop a baseline ADS software system capable of Level 3 and Level 4 automation as a platform for investigation and testing of the ADS safety metrics and envelopes.
- **Objective 4:** Conduct simulation and prototype ADS vehicle testing to demonstrate, verify, and refine safety metrics and envelopes, including human-in-the-loop driving and large-scale computational simulation testing
- **Objective 5:** Demonstrate the real-time safety envelope using on-road tests and test scenarios typical of rural and urban environments, and analyze data from other USDOT-funded project teams to compute safety metrics and comparable safety envelope measures.

1b. Key Partners, Stakeholders, and Team Members. The core UT Austin team is multidisciplinary in nature, with unusual expertise in vehicle design and control and estimation (i.e., algorithms for estimating vehicle motion from available sensor and model information), crash prediction, traffic and ADS monitoring, verification of autonomous systems, and travel behavior. The UT Austin team provides access to a suite of relevant and adequate facilities and equipment for this project, including a fully-instrumented, fully-accessible self-driving (Level 4) vehicle (based on a Ford Fusion passenger car), a driving simulator with six degree-of-freedom motion, and an augmented-reality testbed for intersection safety testing. In addition, to conduct isolated testing of onboard vehicle hardware with simulated models of vehicle dynamics, state-of-the-art equipment is available to conduct such *hardware-in-the-loop* studies.

1c. Challenges, Innovation, and Expected Outcomes. A key challenge is deciding how the dynamic nature of ADS risk should be quantified so that it can be used by regulators, manufacturers, and owners. These challenges can arise due to many factors, such as the presence of human-driven vehicles, motorcycles, bicycles and pedestrians, or when systems approach the boundaries of their operational design domains (ODDs). To address such challenges, this project will develop and test methods and technologies that can quantify safety metrics (which relate directly to evolving risk) in real time. Such metrics are essential if ADS-equipped vehicles (as well as any assistive devices, which may be roadside or remotely located) are to ensure both safety and performance. The project's multi-vehicle and intersection simulations, plus extensive on-road vehicle tests, will demonstrate and validate our methods' effectiveness. We seek to produce leading indicators of ADS safety that can reliably predict lagging indicators, such as crash rates and near-crash/near-miss frequencies under various driving conditions. As reasonable, project products also will support existing methods used in highway safety prediction, by linking to crash modification factors (CMFs) (AASHTO, 2010).

1d. Geographic Area of Demonstration. This project will perform demonstration studies on controlled and uncontrolled streets at UT Austin's Pickle Research Campus. In addition, our ADS vehicle platform will be tested on selected roadways in the City of Austin.

1e. Proposed Period of Performance and Schedule. The proposed project will extend for four years, with effort toward each of the project objectives projected onto the schedule as shown below.



Project Activity	Year 1		Year 2		Year 3		Year 4	
Objective 1	🟧	🟧	🟧					
Objective 2	🟧	🟧	🟧	🟧	🟧			
Objective 3	🟧	🟧	🟧	🟧	🟧	🟧		
Objective 4				🟧	🟧	🟧	🟧	
Objective 5						🟧	🟧	🟧

Table 1. Proposed project schedule

2. GOALS

2a. How this project will address safe integration of ADS into on-road transportation system. For existing road vehicles, speed limits are used to impose control for safe operation on our roadways. The public accepts speed as an indicator of safety, accepting risk for exceeding that level. It is implied that a reasonable human driver has the minimum level of perception and control ability required. To earn a similar level of trust, ADS systems will require explicit and transparent metrics on safety. This project will investigate ADS safety metrics and how they depend on the vehicle and ADS systems operating under typical operational conditions. Candidate safety metrics will be tested and verified through controlled laboratory and field demonstration tests of a prototype AV vehicle with L3 and L4 functionality. Demonstration data will reinforce how defined safety metrics can be used by the public and governmental decision makers to better understand and assess ADS technologies being proposed for public roadway usage.

By defining and quantifying safety metrics, including setting baselines values for safe operation, this project will provide ways to build confidence in users. This includes defining real-time safety envelopes based on metrics related to operating scenarios and environmental conditions. It is difficult to imagine how any ADS can build trust and gain acceptance without meeting acceptable levels of safety as measured by meaningful and transparent metrics, which are applicable over the operational design domain. For this reason, this project will investigate how these metrics and safety envelopes vary during common driving scenarios as well as during more complex situations, such as cross-path intersections (Najm et al 2001).

2b. How this project provides data for safety analysis and rulemaking. This project aims to:

1. *Ensure gathering and sharing of project data*. This project will demonstrate how useful data arises from testing the ADS subsystems, responsible for perception, decision-making, and path-planning and motion control of a vehicle, as well as through on-road testing in typical driving scenarios and under controlled safety-critical edge cases. Our development work will begin by initially providing batched access, but then we will experiment with ways to optimize near real-time access to data during testing.
2. *Leverage demonstration data and results in innovative ways*. We intend to focus on ways to build causal relations between safety-critical behavior of a vehicle and metrics on the safety-related capability of enabling ADS subsystems. We also intend to use controlled experiments to assess whether collision-based safety metrics related to collision modifying factors (CMFs) in the predictive method used for estimating crash frequency for a given roadway configuration (AASHTO, 2019).
3. *Show that data supports safe integration of ADS technologies*. Our adoption of a dynamic safety envelope will provide means to inform the onboard ADS as well as users (and other vehicles) about the safe state of a vehicle. These safety envelopes will be designed to be leading indicators of high-risk events. As a model-basis will be used, these types of safety metrics can be extended to all classes of road vehicles (light and heavy duty).

2c. Collaboration. This project will engage faculty and student researchers with broad backgrounds in engineering, having experience in working with practitioners from private and government organizations. We intend to reach out and work with local and state metropolitan transportation organizations, as well as private companies, to communicate our methods, provide access to testing resources, and provide access to a growing database of data.

3. FOCUS AREAS

3a. Significant Public Benefit(s). We will conduct a demonstration of ADS technology emphasizing means for assessing safety in real-time and will show an ability to quantify the impact on safety measures used to assess public roadways. The significant benefit to the public will be a means for quantifying safety using new leading indicator safety metrics and formation of real-time safety envelopes, as well as a means to relate these metrics to highway safety predictive methods (e.g., use of CMFs per AASHTO, 2010). As such, our project will provide a significant benefit to the public by providing government regulators with methods and tools that allow them to certify that ADS are safe using means consistent with those they use for non-automated driving on public roadways.

3b. Addressing Market Failure and Other Compelling Public Needs. As a University research team, we will take a third-party perspective in defining and evaluating proper safety metrics. Our goal is to provide a transparent, unbiased approach to evaluating safety. Both government regulators and the public are being asked to judge these rapidly evolving technological systems, with seemingly unknown characteristics. We will address the need to identify ways to understand and critically evaluate ADS and how these systems will impact daily use of roadways.

3c. Economic Vitality. As ADS technology continues to grow, there is a need for local business/industry to continue to fill the critical role of maintaining and monitoring the safety of the ground transportation ecosystem. Any evolution in this service industry requires a workforce that can understand and assess advanced ADS, one that does not alienate members of our society (local shops, inspection, etc.) that have traditionally made a living in this space as vehicles take on more ADS. The methods and means for assessing ADS safety proposed by this project will provide a viable basis for supporting a technical ADS-technology workforce. Lastly, the project will support local and national industry by acquiring hardware, software, and other resources made in the USA.

3d. Complexity of Technology. We will introduce an onboard technology that can assess ADS safety metrics in real-time, including a user interface for communicating with drivers the proper level of data content for making safety-critical decisions.

3e. Diversity of Projects. This project will be run through a public University in a city that is rapidly evolving and in need of solutions that will improve the mobility of its people.

3f. Transportation-challenged Populations. Our project is not limited in any way that would limit use or utility of our results to any sector of the population.

3g. Prototypes. This project will focus on a user interface technology prototype that can be integrated into a vehicle with ADS. This interface will support control of the vehicle, but the primary emphasis will be on conveying accurate safety operational information based on define safety metrics.

4. REQUIREMENTS

4a. Research and development of ADS technology. We will formulate and evaluate real-time safety operational envelopes as a core technology for ADS, and use simulation and driving simulator studies to refine underlying safety metrics. Human-in-the-loop driving simulator studies will enable formulation and refinement of safety metrics at L3 and L4 levels of automation, which will be part of follow on road testing with ADS on the Ford Fusion platform.

4b. Physical demonstration. Real-time safety envelopes will be demonstrated and evaluated through on road testing using an experimental Ford Fusion hybrid vehicle platform with L3 to L5 prototype operation capability. Preliminary testing will be conducted using specially-configured test scenario platforms as well as on University of Texas campus roads.

4c. Sensing and data collection/sharing. Data collection and means for sharing data will be refined through preliminary (campus-based laboratory and roadway) testing. The demonstration vehicle includes a full sensor suite with camera(s), radars, GPS, lidar, and an onboard GPU computer. The vehicle includes actuator and control modules to enable automatic steering-by-wire, acceleration, braking. The sensing, computing, and control functions are integrated using the standard ROS programming platform. Perception information can be visualized on-screen for operators inside the vehicle. All data will be saved onboard, and also uploaded to the Secure Data Commons (https://its.dot.gov/data/secure/). We will also make use of the Texas Data Repository (https://data.tdl.org/), a service provided by the University of Texas at Austin.

4d. Platform User Accessibility. The prototype vehicle is a self-contained platform, including all the necessary modules and components for achieving real-time self-driving. Development of an input/output user interface that allows users with varied abilities to input destinations and communicate route information will be integrated as part of the prototyping.

4e. Scalability of the demonstration. The demonstration proposed will focus on development and refinement of critical safety metrics, verified through laboratory testing and transitioning to on-road demonstration. There are not anticipated obstacles to scaling testing beyond the planned initial testing on the University of Texas at Austin campus. We plan to reach out and share our results and methods with local and state agencies. Further, as University researchers and educators at a state public institution, we are well suited and have the resources to convey results to the public and to provide technical exchanges and knowledge transfer to any and all interested parties.

5. APPROACH

This work's ultimate goal is to demonstrate the role safety metrics will play as vehicles with ADS are integrated into public roadways. After motivating the proposed approach, this section provides detailed descriptions of the 1) Technical Approach, 2) Obstacles to Technology Demonstration, 3) Data Sharing and Usage in Safety Evaluation, 4) Project Risks, Mitigation, and Management, and 5) Cost-Share Management Plans.

Motivation. Essential safety measures can be difficult to define, even in well-established systems. Such challenges are compounded for ADS integration into public roadways because of the highly dynamic and evolving state of technology, and the diverse approaches and technologies adopted by companies advancing ground vehicle technology. It can be difficult to establish agreement on metrics that should be used, especially if these rely on transparency of data and the critical assessment and reporting on proprietary system performance. This research study will focus on identifying and formulating key safety metrics, testing methods and associated data collection, and methods for verifying these metrics through simulation as well as laboratory and roadway testing.

System safety typically makes use of both leading and lagging metrics, and both are essential for understanding, regulating, and releasing ADS (Hopkins, 2009; Campbell Institute, 2013; Fraad-Blanar et al 2018). To some extent, lagging metrics - like crash rates per vehicle-year or vehicle-mile traveled across a fleet of OEM-produced vehicles - can be easier to identify, since they relate to clear and generally undesirable outcomes. In contrast, leading indicators generally are proactive, preventative, and predictive measures that can describe system performance and processes. For example, a measure of lateral acceleration relative to the maximal allowable lateral acceleration (road parameter dependent) could define a safety metric during highway driving lane changes. If this metric tended toward a value of 1, this could be a leading indicator of unsafe driving since it would indicate overly aggressive operation, with a high risk of skid or rollover. They can be used to help identify, warn, and avoid or control vehicle and roadway crash risks.

Requirements. Leading indicators for ADS safety should be useful in identifying ADS crash risks so that action can be taken *before* passengers and other roadway users perceive a safety violation, before roadmanship rules are violated, and before a crash takes place. Ideally, leading indicators should also be actionable, so that communications within the ADS and/or to other parts of the transport system enable desired safety improvements dynamically, in real time. It is not clear, for example, how measuring miles-per-ADS-disengagement provides any such causal insight for ADS users, manufacturers, and regulators. However, collecting the data required for this metric's computation is fairly straightforward. It is essential to have safety metrics that are computable while also providing insight into how system improvements can and should be made. A simple example of a traditional vehicle safety metric that meets these requirements is the *static stability factor*.

<u>*Example: Static Rollover as Safety Metric.*</u> The classical static stability factor (SSF) can be used to illustrate definition and formulation of a quantifiable safety envelope. Vehicle characteristics, operating conditions, and environment all play a role in this simplified measure of rollover propensity. A rollover safety envelope is formed by how a vehicle's SSF depends on lateral acceleration, a_y, and roadway slope, ϕ, as shown in Figure 1. The upper envelope is found for a vehicle with high performance turning ability, while the lower envelope corresponds to a heavy truck.

The real-time rollover safety of a particular vehicle operating on a specific roadway could be evaluated against this metric by using data measured from key operational and environmental conditions. In this case, vehicle speed, roadway curvature, and the slope are sufficient to assess the relative rollover safety. This particular measure of rollover safety, of course, is limited since it is defined for static rollover. Clearly, a heavy truck has a lower SSH than a sports car.

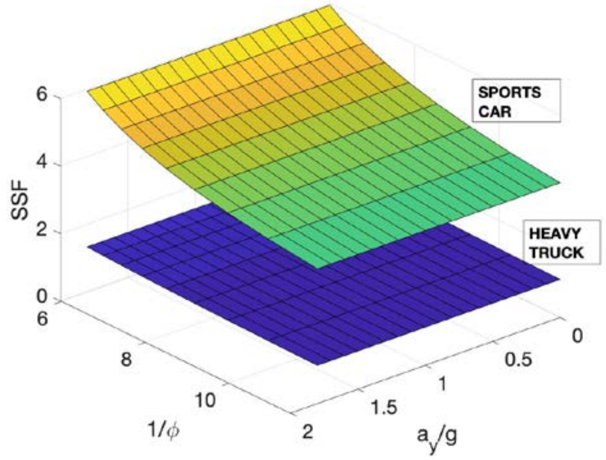


Figure 1. Plot of SSF versus normalized lateral acceleration and inverse slope. This is an example of how a safety metric can be defined that accounts for key operational and environmental conditions, in this case using a simplified physics-based model.

The underlying basis of the classical SSF is a (static) limit condition, found from a simplified physical model. While limited, it illustrates how the operating conditions of a vehicle (forward velocity) and the environment (road slope) directly inform a safety metric. It also should be made clear that there is no consideration of the human driver. This is not uncommon. Metrics for vehicle handling stability, such as understeer or yaw velocity gain, are *open loop* (steering) characteristics. It is usually assumed that these metrics convey how effectively the average human driver can control the vehicle. There are more advanced analyses incorporating a human that allow performance and stability metrics to be defined for the combined human-vehicle system under specific types of operations (like lane following or turning).

Defining safety metrics for ground vehicles with ADS is much more complicated because the vehicle motion control now integrates with the more advanced capabilities of *perception* and *decision-making*. Figure 2 illustrates the integration of these systems at a conceptual level, including the role of the human in the control loop as well. The added complexity of ADS is essential for monitoring highly dynamic changes in the environment and in automated vehicle operation over a wide range of conditions.

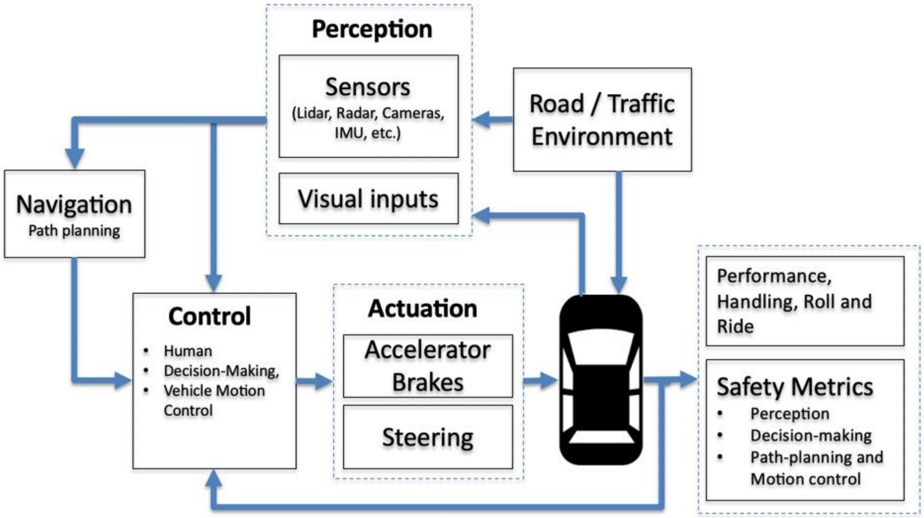


Figure 2. High-level schematic integrating human and ADS driving of a ground vehicle. Typical metrics on performance, handling, and ride to be supplemented by Safety Metrics which would include those associated with perception, decision-making, and vehicle motion control. These could be defined for a human driver or for a given ADS system.

A vehicle is expected to have many safety metrics related to performance, handling, and ride. Similarly, perception, decision-making, and vehicle motion control may have multiple safety metrics depending on the mode of operation and the road/environment characteristics. Safety envelopes are thus proposed for ADS, and will depend on metrics for perception, decision-making, and vehicle motion control, and thus vary with time as operational and environmental conditions change. Dynamic ADS safety envelopes can be monitored and reported in real time. Consequently, it is essential that we first define safety metrics related to ADS perception, decision-making, and vehicle motion control capability. These metrics and the real-time envelopes to be formulated will provide a basis for comparing and assessing the safety characteristics of different vehicles and ADS platforms.

5a. Technical approach.

The proposed approach is comprised of the five objectives listed in the *Executive Summary*. Each of these objectives is described below, with discussion of methods to be used and expected outcomes. Figure 3 illustrates the project flow, and various key terms are defined below.

Vehicle status: refers to capabilities, conditions, and health states of the vehicle sensors and actuators

Environment: deterministic elements and conditions of roadway (including traffic signs and signals, number of lanes, road curvature, cross slope and grade, road surface friction level, lighting, weather conditions). It can be assumed that the ADS knows the environment it will be entering based on reliable sources such as GPS and maps.

Scenario: stochastic factors in a given environment (including surrounding traffic, pedestrians, and other random factors that can be blended into a given "environment"). Note that it is assumed that ADS may not have a complete knowledge about the scenario it is entering because of its random variations and ADS perception incapability.

Driving condition: measure of combined environment and scenario

Safety case: specific safety-critical scenario in highway, city, rural, and neighborhood driving. Any cases will be clearly defined.

Safety metric: a quality of a vehicle and/or ADS system related to safe operation.

Safety envelope: a dynamic safety metric defining safe operation boundaries, including those defined for a specific safety case.

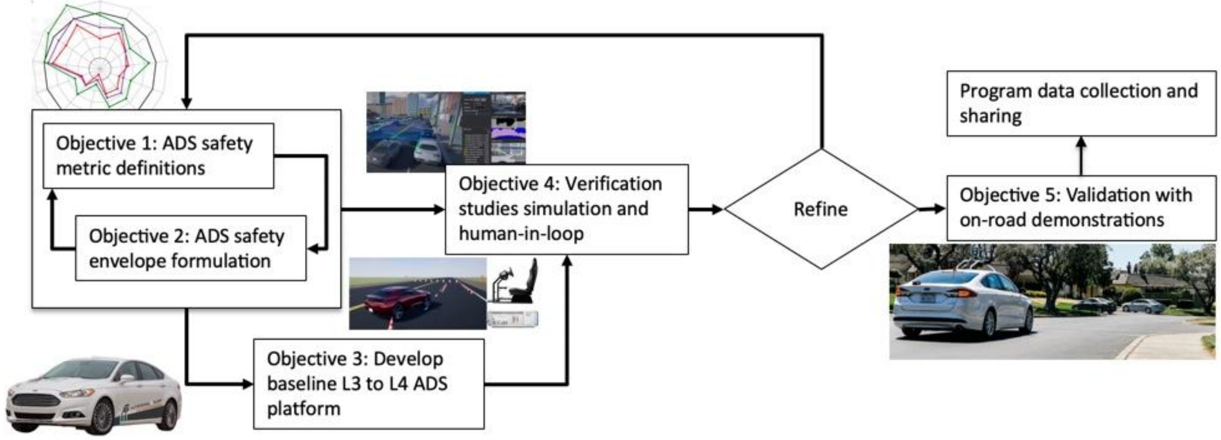


Figure 3. Flow of project objectives toward on-road demonstration

Objective 1: Investigate, develop, and implement methods for defining reliable, accurate, and quantitative real-time ADS safety metrics

Background and Motivation. While vehicles with ADS are highly complex, safety metrics should be transparent and well understood by all stakeholders, engineers, regulatory decision makers, and maybe even by the public. Recent studies on safety validation of ADS have demonstrated how safety metrics can be formulated that relate to driving scenarios (e.g., Eckstein and Zlocki, 2013; Asljung et al 2016; Junietz et al 2018). Given the wide range of scenario types that either human drivers or ADS are expected to encounter, one approach is to define a metric for a specific safety scenario, such as the time-to-collision or brake-threat-number (Asljung et al 2016), both useful as leading indicators. In contrast, Junietz et al (Junietz et al 2018) proposed a single *criticality metric* to quantify a range of accident types using measures on the complexity of the trajectory required in different driving scenarios. These past works have not sought to reveal the causal role of ADS subsystems in safety-critical operations.

This objective will focus on defining safety metrics related to the key ADS characteristic technologies of *perception*, *decision-making*, and *vehicle path-planning and motion control*. Dynamic safety envelopes in **Objective 2** will be formulated with dependence on metrics related to these subsystems. The investigation proposed here is to formulate metrics that quantify how ADS capabilities influence safety-critical operation. These metrics could be but are not solely related to functional reliability, which is presumably part of any ADS realization. For example, it is assumed that any ADS system will be able to identify faults in these complex systems. The intent here is on methods that would enable estimating whether changes in perception capability, for example, will impact a safety envelope and quantify such an impact.

Methodology. ADS subsystem metrics will be influenced by roadway conditions, weather, lighting, and traffic conditions. Some factors (such as lighting, weather and road conditions) are stochastic in nature and cannot be controlled during normal operations. We refer to these as “environmental inputs”. Roadway configuration is also an environment variable, although it is more deterministic. The following refers to a scenario based on the type of driving task required.

As we describe or refer to the key ADS safety metrics, we will assume that there will be dependence on scenario and environmental conditions. In this project, we will refer to ways to quantify how these factors influence the safety metric defined. Some reference can be made to recent studies such as Junietz et al (Junietz et al 2018), who defined a criticality metric as way way of quantifying the complexity of a maneuver for a given driving scenario. Alternatively, Damerow et al (Damerow et al 2016) came up with ways to quantify and classify different situations based on trajectory. These are two examples of way we can come up with a quantifiable scale to capture the effect of scenario in order to provide a basis for quantifying a relation with defined safety metrics. In a similar fashion, the same should be done with respect to variables related to environment. Coming up with useful measures of this form represents a key step under this objective. This will aid how we categorize and classify the series of testing procedures designed for safety-critical study cases typical of highway, city, rural, and neighborhood driving.

<u>Perception Safety Metrics.</u> ADS perception depends on multiple sensors (lidar, various cameras, radar, ultrasonics) and their characteristics as well as algorithms for processing and learning. We seek an objective way to quantify overall ADS perception capability (and limitations), especially as environment and scenario conditions vary. This can be particularly challenging because some knowledge about the latter (as inputs) is required from the perception system as well, and this dilemma is usually overcome by ground truth testing (Krotkov et al 2007; Johnson et al 2009; Moorehead et al 2010),

and the distinction between system-level and sensor-level performance assessment has been demonstrated (Dima et al 2011). It can be useful to retain both measures of performance, especially to isolate *Perception Confidence* (PC) for an ADS, which can depend on vehicle status under a given driving condition.

We will investigate error, error rate, and/or time delay measures, since these can directly impact key metrics, like distance to an obstacle or interpretation of an object or sign. Standard techniques from statistical machine learning are used to compare the outputs of the different components of a perception system to ground-truth data. Performance measurements rely on false-positive and/or false-negative detection rates, receiver operating characteristic (ROC) curves, precision/recall curves (PRC), confusion matrices and area under the ROC curve (AUC) (e.g., Fawcett 2003; Fawcett 2006; Viggh et al 2017). During laboratory testing it is possible to gauge the effect of degradation due to environment or device changes. For instance, the perception metric may automatically decrease if a camera malfunction is detected.

Another measure that may be useful can be defined from the concept of hazard perception; a metric used for assessing human drivers. When assessed for human drivers, hazard perception has been shown to directly influence a driver’s ability to avoid collisions - a good *leading* indicator (Horswill 2016; Wetton et al 2011). Since we will be demonstrating using a prototype ADS system, it will be possible to investigate ways to experiment with how hazard perception features can be implemented, and the impact on safety metrics evaluated.

Our efforts here will lead to a method that can calculate PC that quantifies the level of perception accuracy for a given ADS vehicle status under a driving condition.

<u>Decision-making Safety Metrics.</u> The decision-making functionality needs to coordinate different behaviors as a vehicle encounters diverse types of road scenarios, as well as making use of navigational needs and available information. These are highly complex software systems primarily developed using a data-driven, machine-learning approach, and solutions vary among different ADS developers which are mostly proprietary. Verifying these complex solutions and their operation within ADS systems has given rise to a challenging verification and validation problem. Developers adopt different approaches to ensure the final products meet their specifications and requirements. There do not appear to be any metrics defined that relate to safe operation under real conditions, with most assessments tied to overall testing of the vehicle in an attempt to prove the learning algorithms tend toward safe operation over time.

An alternative way to assess the impact of decision-making capability is needed from the standpoint of overall safety. In most practical cases, detailed models, data, or test results may not be made available to end users or independent evaluators of an ADS system. For this reason, we need to build models or approximations that capture dominant decision-making features, particularly with respect to measures of the environment and scenario. This approach would enable a pathway to independent assessment without requiring proprietary information, while providing some causal link between performance and relevant operating conditions.

Our preliminary approach for developing a decision-making metric will take advantage of the development of a prototype ADS platform in **Objective 3** (see Figure 2). Knowledge about the specifications, requirements, and detailed implementation under Objective 3 will provide a reference for assess our own models of decision-making capability. We expect decision-making takes the form of a finite-state machine, and conditioned on scenario, able to take on a preferred state (or driving mode) based on sensory (perception) inputs. For example, it has been shown to be effective that models with statistical characteristics can be formulated (e.g., based on naturalistic human driving data) to effectively describe behavior in lane-changing maneuvers (Zhao et al 2017). This suggest that these types of models could be used to formulate quantitative metrics on decision-making as well. Such a metric could thus address the probability that a certain operation can be accomplished, providing a way to convey *Decision-Making Confidence* (DMC) for the prototype ADS based on specific scenario and environment conditions.

Path-Planning and Motion Control Safety Metrics. Of the three key ADS subsystems, path-planning and motion control (PPMC) capability relies on methods that have been applied and tested in production ground vehicles. As such, there are well-established approaches that relate safe operation to characteristic properties of this subsystem (comprised of steering, braking, suspension, powertrain, etc.). Path-planning and motion control make use of steering, throttle, and braking actuation to effect desirable dynamics of the vehicle.

As in the two other ADS subsystems, we seek a quantitative metric that can provide a measure of *Path-Planning and Motion Control Confidence* (PPMCC). This will enable quantifying how ADS PPMC capability and limitations impact a dynamic safety envelope subject to scenario and environmental conditions. The methods used will make use of a vehicle dynamics, model-based approach to compute the PPMCC in real time. For example, the PPMCC will provide a measure of confidence that the ADS can achieve a planned vehicle path with required motion control safely, taking into account a suitable level of known vehicle system dynamics and driving condition.

One approach to consolidating the influence of these different factors is by selecting relevant measures based on the dominant ‘mode’ of behavior. For example, in an emergency braking scenario the critical factors that measure the capacity of the PPMC may consider brake response and available brake friction. A dynamic model of the vehicle system with combined steering and braking dynamics is sufficient for this purpose. Under more extreme conditions, a more complex model with roll motion could be considered to answer questions about the capacity in the context of a safety metric. We will investigate useful ways to form combinations of metrics related to path-planning and the vehicle dynamics and controls capacity to form a robust metric that can be related to safe operation.

Application to an ADS Emergency Braking Scenario. A simplified case study is presented here to illustrate how the three ADS subsystem safety metrics may be defined and quantified, how they depend on measures of scenario and environmental conditions, and thus how these metrics can provide important safety-related information for online use and for post-analysis. A simplified braking scenario is summarized in tabular form in **Table 2.** The analysis provided shows that it is possible to identify safety metrics and which in turn can be used to inform dynamic ADS safety envelopes. For example, by the braking capacity required to safely stop can be compared with (estimated) measures of maximum braking capacity to define one component of a dynamic safety envelope.

Emergency Braking Scenario - Prototypical Safety Metric Generation			
Scenario and Environment Features	**ADS subsystem action**	**Safety-related metric**	**Safety Envelope** Is specified metric within safe values?
Stop sign, road geometry, road conditions	Perception: Recognizes a stop sign; Measures road features	Measure of errors or error rates in perception	ROC/PRC based measures on error rates
Road rules specify stop action	Decision-Making: Bring vehicle to a stop	Measure (probability) that PPMC can provide proper control to stop	Relative measures on path-plan, actuator ranges
Road users; tire-road friction	PPMC: Determines control actions required to stop (reach a safe state)	Brake capacity needed to stop as required	Steering and/or brake limit measures

Table 2. *Emergency Braking Scenario - Prototypical Safety Metric Generation*

It is expected that all safety-critical scenarios in the ODD will need to be analyzed in this type of fashion to compose safety metrics. As shown in the last column, these metrics provide the information needed to define useful safety envelopes (**Objective 2**).

Ultimately, it is necessary to verify that any such safety metrics can serve as *leading indicators* for ADS operating under real world conditions. This assessment will fall under the work described in **Objective 4**, which will use simulation studies, studies in a human-in-the-loop driving simulator, and controlled testing on the AV/ADS prototype system to assess and refine the preliminary ideas described here.

Expected Outcomes. This objective will result in system level safety metrics for each of the key ADS capabilities, quantified with respect to measures for driving scenario and the environment. A systematic methodology will be formulated that can be used to develop safety metrics that provide new and insightful types of data that can be collected and analyzed in new ways to understand how safety-critical behavior of vehicles related to the key ADS subsystems. As such, these safety metrics will form the causal basis for how dynamic safety envelopes developed through **Objective 2** related to scenario and environmental measures.

Objective 2: Develop and implement methods for generating real-time and dynamic safe ADS operational envelope based on key safety metrics

Background and Motivation. ADS Safety envelopes define and quantify limits and conditions within which the ADS subsystems can be operated to conform with safety requirements under which these vehicles will be licensed to operate. The limits and conditions are imposed on the safety metrics from **Objective 1**. The safety envelopes should be defined as *leading indicators* of unsafe roadway events. Leading indicators help identify risks and allow action to be taken before accidents and injuries take place, and can be defined across a wide risk spectrum. Focus here will be on high-risk leading indicators. These must be defined and shown to address concerns the public and government agencies have with regard how vehicles with ADS can safely operate on roadways.

Methodology. Safety envelopes can be defined with reference to specific safety-critical events. For example, past work reported in the literature describes measures of time and distance to collision (e.g., Schwarz, 2014). Other investigations have examined measures on intensity of evasive action required to avoid a collision. There have also been definitions and use of surrogate safety measures or indicators (Gettman and Head, 2003; Gettman et al 2008; Mahmud et al 2017) in traffic conflict analysis. These studies can provide insight on important factors when taking more a perspective that can be useful when looking at the influence of a large-scale distribution of vehicle with ADS. The work under this objective will begin with model-based studies to guide the definition and evaluation of various measures, particularly those that lend themselves to test and validation. We seek defining safety envelopes that have a direct causal relation to the ADS subsystem metrics defined under **Objective 1**, with an implicit dependence on scenario and environmental conditions. For example, in the scenario described in **Table 1**, it may be desired to examine how a braking measure is influenced by the PPMC metric. Within the context of that example, there are three explicit safety envelopes that would inform ADS emergency braking: 1) a metric on perception, as regards ability to interpret, say, a stop sign or distance to the region where the vehicle must be stopped, 2) a metric on decision-making, possibly a probability that the correct actions are taken, and 3) a metric on actual braking capability, possibly gauged with available braking force to indicate whether the braking action can be accomplished within the stopping distance available.

We will work through the known safety measures known to be useful indicators of critical events, such as collisions. For example, time-to-collision, post-encroachment time, and time gap. The latter two are common in rear-end collisions and in angled mergers. A much different and more difficult scenario for AVs and ADS, is a left turn into a crossing path. In general, crossing paths are difficult for humans as well (Najm et al 2001). In this case, a safety envelope examine a dynamic reachability measure (which factors in the controlled trajectory of the vehicle) against some probabilistic measure, say, of traversable ‘traffic gaps’ in in the roadway (dependent on perception). Any of these example safety envelopes need to be quantified based on expected behavior of the vehicle, which typically comes from a simplified model. It is also expected that there is some uncertainty associated with these estimates given that there are unknowns and/or stochastic effects.

Another good example of an ADS safe operational envelope is a *safe speed limit* (Johnson et al 2009; Moorehead et al 2010). By taking into account confidence levels on ADS safety metrics as well as possibly probabilistic estimates of collision, it is possible to provide feedback on suitable automation level. In this way, the ADS safety envelope is dynamically determined by a function (or functions) that can take into account the inherently coupled relationship among the perception safety metrics, decision-making safety metrics, and the PPMC safety metrics. As a result, these metrics all form a cohesive data set that informs safety.

Expected Outcomes. The work proposed under this objective is distinguished from that under Objective 1 in order to emphasize that a safety envelope refers to specific measures related to a safety-critical variable. Under this objective, a catalogue of relevant safety envelopes will be identified and associated with a known set of safety-critical events, particularly those associated with near-crash situations and scenarios. Through model-based studies and physical validations, relations will be established to the three key ADS subsystem safety metrics (as developed under **Objective 1**).

Objective 3: Develop a baseline ADS software system capable of Level 3 and Level 4 automation as a platform for investigation and testing of the ADS safety metrics and envelopes

Background and Motivation. The design of safety metrics and envelopes, and their use in providing useful data during verification testing and on-road demonstrations will make use of an autonomous HEV Ford Fusion platform that is available in the Mobility Systems Laboratory at UT-Austin (Acquired from AutonomousStuff, Morton, Ill; www.autonomoustuff.com), as shown in Figure 4. This vehicle platform is street-legal and fully equipped with perception, computation, and actuation hardware for achieving autonomous driving from Level 3 to Level 5. Perception hardware includes cameras, radars, differential GPS, lidar, a GPU computer, as well as automatic steering, acceleration, braking modules. The perception, computing and control are programmed and operate using ROS (Quigley et al 2009).

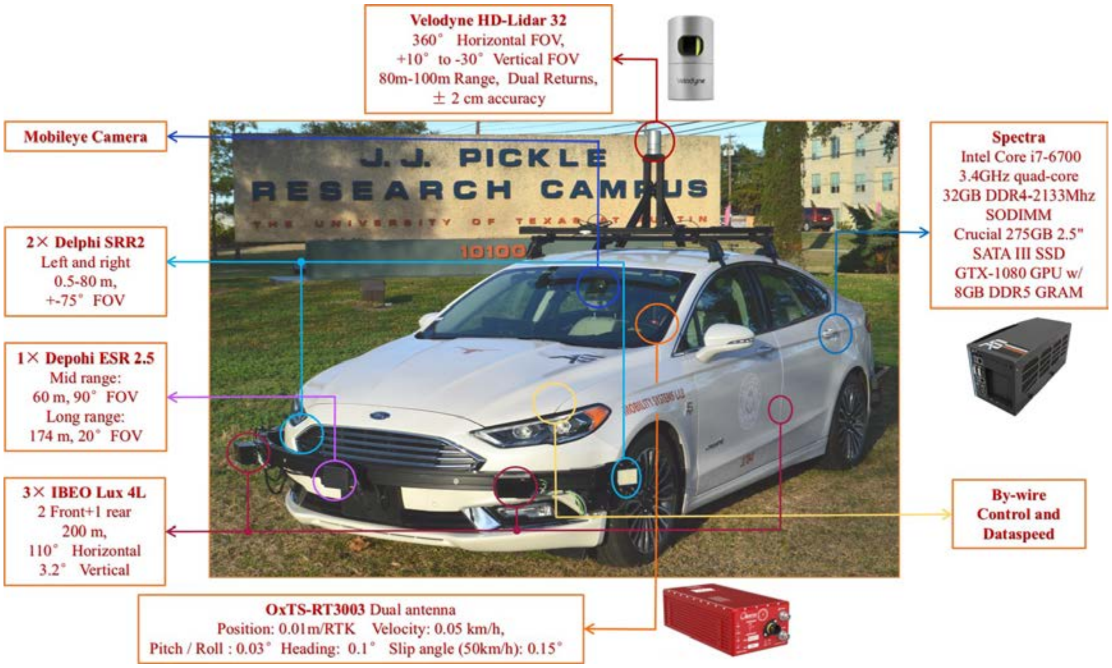


Figure 4. Autonomous HEV Ford Fusion platform to be used for laboratory and on-road demonstrations (Mobility Systems Laboratory, The University of Texas at Austin)

Methodology. A baseline ADS software system capable of achieving Level 3 and Level 4 automation will be developed using the fully-accessible Ford Fusion vehicle platform. As part of this development, we will create a user input/output interface that allows users to input a new destination or communicate route information generated by the ADS. The development of the prototype ADS system will be staged, focusing on specific ODD at L3 and L4 levels of automation. The intent is to assess key safety metrics per Objectives 1 and 2, as such the intent is to have a design allowing targeted operations. One advantage of this ‘open source’ development is that the specific code for the ADS subsystems will be available for baseline assessment of safety metrics.

Onboard processing of the safety metrics and targeted safety envelopes will be accomplished in near-real time, demonstrating the capacity to provide the user with this information. Data collection functions will also be realized.

Expected Outcomes. The principal outcomes from this objective is a working ADS platform with an open-source design that provides data in the form of safety metrics. These safety metrics, as developed in Objectives 1 and 2, will provide an online measure of safety for different safety-critical operations (available on the user interface) and will be incorporated into data gathering protocols and reports.

Objective 4: Conduct simulation and prototype ADS vehicle testing to demonstrate, verify, and refine safety metrics and envelopes, including human-in-the-loop driving and large scale computational simulation testing

Background and Motivation. Complexity of the driving task prevents us from conceiving of a single measure of safety that can cover all expected and unexpected scenarios, as well influences from environmental conditions. The safety of vehicles with ADS needs to be transparent, even when encountering so-called ‘edge cases’, situations that fall outside of the realm of what a vehicle ADS system has been programmed or trained to deal with. The aim of this objective is to test safety metrics and safety envelopes under development so they can provide insight into how an ADS system is managing risk. We can begin with various forms of modeling and simulation studies to investigate the efficacy of these safety metrics over a wider range of conditions than possible with a physical test vehicle. These studies can assess sensitive, exploring the effect of changes not only in the ADS subsystems but also in the scenario and environmental conditions. Subsequently, a prototype ADS vehicle platform can be used in controlled laboratory studies to provide additional insights, so that safety metrics can be refined before deployed for on-road validation.

Methodology. The methods and tools to be employed in this part of the proposed project, as illustrated in Figure 5, include:

a) Modeling and simulation platforms: A variety of modeling and simulation platforms will be employed. To begin with, the PIs have expertise in using modeling and simulation platforms like CarSim and MSC.Adams, which can be used to verify simpler models used in control-oriented models and models used to design safety metrics. We will also adopt the industry-grade ADS/AV software platform Metamoto, which allows detailed design and simulation for vehicles with ADS platforms. This platform allows a user to include sensor models, design driving and traffic scenarios, and manages simulations studies with variations in all key systems. This platform will provide simulated data that can be used to assess proposed safety metric and envelopes, for example, before we test on a real platform.

b) Driving simulator: Proposed algorithms for the ADS prototype can be tested on a human-in-the-loop simulator to assess the influence of human interactions with proposed safety metric and envelope indicators relative to simulated driving and environment conditions. A user interface will be prototyped and refined within this testing platform, supporting implementation on the Ford Fusion test vehicle through **Objective 3**.

c) Launchpad: The AB Dynamics launchpad system is a unique moving platform that can be remote-controlled or synchronized for motion with a test vehicle. In testing and verification studies in the laboratory, the launchpad can be used to provide assessment of perception as well as decision-making metrics. In this configuration, the prototype ADS vehicle would be configured for vehicle-in-the-loop testing (in lab, on chassis dynamometer) so ADS subsystems could be characterized.

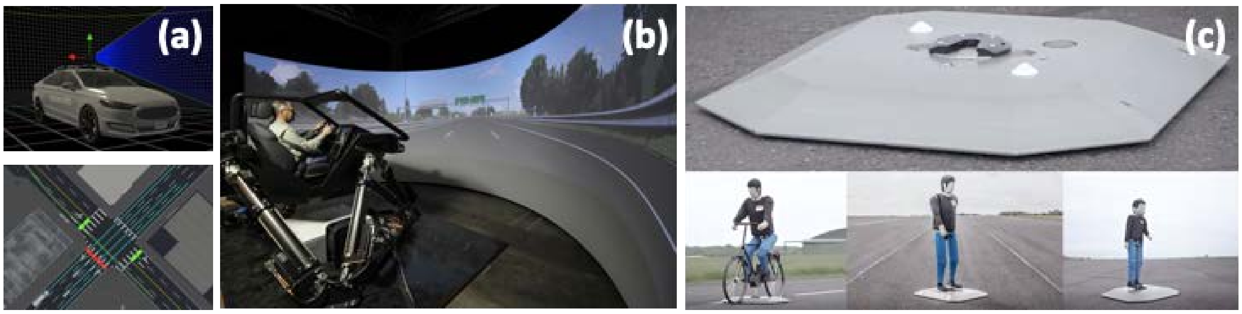


Figure 5. (a) Industry-grade AV/ADS simulation platform (Metamoto, Inc.) (b) Human-in-the-loop driving simulator (Mobility Systems Lab, UT-Austin) (c) AB Dynamics, Inc. LaunchPad moving platform.

During testing and verification studies, we will engage in repeated a test/evaluate/refine process (per Figure 2), exploring the influence of different simulated driving scenario and environment conditions. These studies will be conducted in cooperation with parallel use of the Metamoto platform, as well as other high-performance computing platforms available at the University of Texas at Austin. Monte Carlo studies and investigation of Extreme Value Theory methods will be used explore how effective the safety metrics and proposed safety envelopes, which would stream as data from an ADS-enabled vehicle, serve as leading indicators, particularly for collisions.

Expected Outcomes. Our testing and verification process will evaluate and guide refinement of the methodology by which we define ADS subsystem safety metrics. It is expected that the validity of these metrics will provide insight into the safety of a given ADS platform. The combined use of physical testing and different types and levels of simulation will generate test results and extensive data related to typical driving scenarios as well as various edge cases. These studies will also provide results from extensive simulation studies to simulate the generation of real-time safety metrics and envelopes, providing a way to directly relate risk level to driving conditions. Finally, we expect to provide initial results into whether the statistical analysis of these metrics, as leading indicators of safety, can also be related to lagging indicators, and particularly frequence of crashes. As such, this could provide a way to inform existing methods in highways safety design to account for the introduction of ADS at a given roadway configuration.

Objective 5: Demonstrate the real-time safety envelope using on-road tests and test scenarios typical of rural and urban environments, and analyze data from other USDOT-funded teams to compute safety metrics and comparable safety envelope measures.

Background and Motivation. The demonstration of a safety-metric enabled ADS prototype platform will provide insight into how this new class of operational data affects user-response, as well as how and whether the safety metrics lend to a causal understanding of behavior. For the purposes of this proposed study, on-road demonstrations will be confined to the Pickle Research Campus at The University of Texas at Austin. This campus provides a somewhat controlled environment, although the roads are not closed to other traffic, including pedestrians, bicycles, vehicles, etc. Some areas with unique roadway configurations can be closed off to traffic for controlled study at intersections, merging behavior, and crossing path turns, for example. These experiments are needed to assess full deployment of the methods and ADS levels, allowing for a limited ODD development (i.e., the prototype can have controlled sequences, but not fully operational for L4, for example).

Methodology. We will design test scenarios involving the prototype ADS Ford Fusion operating in typical scenarios. Four typical roadway configurations sampled from the Pickle campus are shown in Figure 6. These and other possible sites can provide a preliminary basis for demonstrating the safety metrics related to: i) emergency braking, ii) gap detection and safe turning in a cross flow, iii) safe merging, iv) intersection interactions, etc. In all of these, the launchpad system can be used to insert a moving obstacle in the form of a pedestrian, cyclist, or vehicle.

These test scenarios will provide an opportunity to share data on typical scenarios, providing complete access to the design of the ADS platform as well as definitions of the safety metrics. In addition, the use of the launchpad can allow us to test edge cases, including near misses and actual collision (with soft body targets). We expect that the demonstration testing and the types of experiments to be conducted will provide a wealth of data useful to the community of researchers and to those interested in use of quantifiable safety metrics. Nevertheless, we will seek to apply the methods beyond the demonstration testing on the Pickle campus. First, we will explore some excursions into public roadways provided we can overcome some of the administrative obstacles for testing a University-owned (and insured) research vehicle. A more fruitful avenue will be to collaborate with other sponsored projects and share metric design and monitoring so that we can assess data that has been collected under real-world conditions. There are opportunities for this type of collaboration within the state of Texas.

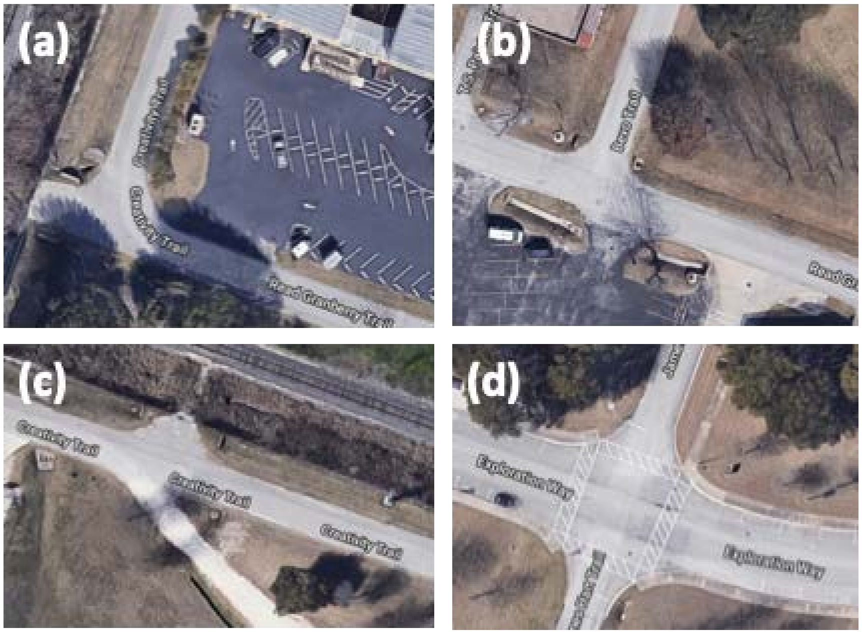


Figure 6 (a) Right-angle turn (b) Cross path (c) Merging (d) 4-way intersection

Expected Outcomes. The efforts under this proposed objective will lead to a series of on-road demonstration data sets targeting specific roadway configurations, but with multiple scenario variations, changes in weather conditions, insertion of moving obstacles, and other effects. Data from these experiments will be catalogued, and will prominently include records of real-time safety metric variations as well as safety envelopes related to specific safety-critical measures.

5b. Obstacles to Technology Demonstrations. The test vehicle to be used for on-road testing is insured for operation on campus roads, and is street legal for manual operation on all roads. The State of Texas passed Senate Bill 2205 in September of 2017 which allows for driverless vehicles to be used on highways as long as they comply with all traffic laws, are equipped with video recording devices, and are insured just like other cars. These vehicles must have state registration, and the “manufacturer” (presumably the University) will be responsible for any traffic laws violated or any car wrecks. Given the scope of the project, however, there are no obstacles to completing the proposed work, as all initial testing will be conducted on the University of Texas at Austin campus.

5c. Data Sharing and Usage in Safety Evaluation. We will set up and maintain methods for batched and real-time data storage and demonstrate its use in safety analysis for mobility applications.

5d. Project Risks, Mitigation, and Management. As designed, there are not perceived risks that would impede progress should this project be funded. The project team is made up of engineering faculty with experience in designing, implementing, and managing research and development projects.

5e. Cost-Share Management. The Dean of the Cockrell School of Engineering has provided a letter of commitment to support this project with $50,000 in equipment cost-share.

References

AASHTO, 2010. The Highway Safety Manual, American Association of State Highway Transportation Professionals, Washington, D.C., http://www.highwaysafetymanual.org.

Cummings, M.L., Britton, D. 2018. Regulating Safety-Critical Autonomous Systems: Past, Present, and Future Perspectives. Everyday Robots, Ed: Richard Park, in press.

Czarnecki, Krzysztof. 2018. Operational Design Domain for Automated Driving Systems: Taxonomoy of Basic Terms. Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, Canada.

Dima, C., Wellington, C., Moorehead, S., Lister, L., Campoy, J., Vallespi, C., Jung, B., Kise, M., Bonefas, Z. 2011. PVS: A System For Large Scale Outdoor Perception Performance Evaluation. 2011 IEEE International Conference on Robotics and Automation. Shanghai, China. May 9-13. pp. 834-841

Dyreborg, J. 2009. The causal relation between lead and lag indicators. Safety Science. 47, 474-475

Eckstein, L., A. Zlocki. 2013. Safety Potential of ADAS – Combined Methods for an Effective Evaluation. 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV): Research Collaboration to Benefit Safety of All Road Users. Seoul, South Korea. p. 7.

Fagnant, D.J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transp. Res. Part A Policy Pract. 77, 167–181.

Fawcett, T. 2003. ROC graphs: Notes and practical considerations for researchers. HP Labs Tech, Tech. Rep. HPL-2003-4

Fawcett, T. 2006. An introduction to ROC analysis. Pattern Recognition Letters. Vol. 27, pp. 861-874.

Fraade-Blanar, L., Blumenthal, M.S., Anderson, J.M., Kalra, N. 2018. Measuring Automated Vehicle Safety: Forging a Framework. RAND Corporation Report, RR2662.

Gettman, D., Head, L. 2003. Surrogate safety measures from traffic simulation models: final report. Federal Highway Administration, FHWA-RD-03-050.

Gettman, D., Pu, L., Sayed, T., Shelby, S. 2008. Surrogate Safety Assessment Model and Validation: Final Report. Federal Highway Administration, FHWA-HRT-08-051.

Horswill, M.S. 2016. Hazard Perception in Driving. Current Directions in Psychological Science. Vol. 25(6), 425-430.

Johnson, D. A., Naffin, D.J., Puhalla, J.S., Sanchez, J., Wellington, C.K. 2009. Development and implementation of a team of robotic tractors for autonomous peat moss harvesting. Journal of Field Robotics. vol. 26, no. 6-7. pp. 549–571.

Kalra, N., Paddock, S.M. 2016. Driving to safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability? Transportation Research, Part A, 94, pp. 182–193.

Koopman, P., Wagner, M. 2017. Autonomous Vehicle Safety: An Interdisciplinary Challenge. IEEE Intelligent Transportation Systems Magazine, Spring 2017, pp. 90-96.

Krotkov, E., Fish, S., Jackel, L., McBride, B., Perschbacher, M., Pippine, J. 2007. The DARPA PerceptOR evaluation experiments. Autonomous Robots. Vol. 22, no. 1, pp. 19–35.

Li, T., K. Kockelman. 2018. Valuing the Safety Benefits of Connected and Automated Vehicle Technologies, In Kockelman & Boyles (eds.) Smart Transport for Cities & Nations: The Rise of Self-Driving & Connected Vehicles. Create Space, Amazon.

Mahmud, S.S., Ferreira, L., Hoque, M.S., Tavassoli, A. 2017. Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs. IATSS Research. Vol. 41. pp. 153-163.

Moorehead, S. J., Wellington, C.K., Paulino, H., Reid, J.F. 2010. R-Gator: an unmanned utility vehicle. Proceedings of the SPIE. pp. 769215(1-12).

Najm, Wassim G., Smith, John D., Smilth, David L. 2001. Analysis of Crossing Path Crashes, Report No. DOT-VNTSC-NHTSA-01-03, July 2001.

Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R. and Ng, A.Y., 2009, May. ROS: an open-source Robot Operating System. In ICRA workshop on open source software (Vol. 3, No. 3.2, p. 5). (http://www.ros.org)

Road vehicles — Functional safety. ISO 26262:2011

Schwarz, C. 2014. On computing time-to-collision for automation scenarios. Transportation Research Part F: Traffic Psychology and Behaviour.
(27), Part B, pp. 283-294.

Viggh, H.E.M., Shah, D.C., Cho, P.L., Armstrong-Crews, N.L., Nam, M., Brown, G. 2017. Shared Perception for Autonomous Systems. Lincoln Laboratory Journal. Vol. 22(2), pp. 91-114.

Zhao, Y., K. Kockelman. 2000. Behavioral Distinctions: The Use of Light-Duty Trucks and Passenger Cars. Journal of Transportation and Statistics 3 (3).

Zhao, D., Lam, H., Peng, H., Bao, S., LeBlanc, D.J., Nobukawa, K., Pan, C.S. 2017. Accelerated Evaluation of Automated Vehicles Safety in Lane-Change Scenarios Based on Importance Sampling Techniques. IEEE Transactions on Intelligent Transportation Systems. Vol. 18(3), pp. 595-607.