Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information

Proof-of-Concept Demonstration Report

FHWA-HOP-21-040 February 2023

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

Automated driving systems (ADS) and cooperative ADS will transform how vehicles interact with each other; other travelers; and transportation infrastructure, communications infrastructure, information systems, and system management and operations strategies. Infrastructure owner-operators (IOOs) have been grappling with questions about how ADS will interact with the transportation system—and what IOOs can do to prepare. Uncertainty about the timing of ADS technology development has made this preparation a challenge. The Federal Highway Administration has been exploring automated vehicles (AVs) to understand national automation readiness and to help facilitate AV integration into the transportation system. This exploration includes assessing data and information needs for AVs and identifying practice-ready information and tools to guide AV integration.

A key aspect of development of ADS behavior and safe integration of AVs into the transportation system is access to data about traffic laws and regulations. This report details the challenges of establishing an ADS-ready traffic laws and regulations database, and accessing and exchanging requirements to support the sharing and consumption of the information within the ADS ecosystem. It also identifies the basic requirements for collaboration among State and local traffic code stakeholders, as well as ADS behavior subject matter experts.

This report will be of interest to CDA system developers, analysts, researchers, and application developers.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No:	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HOP-21-040		

4. Title and Subtitle Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information – Proof-of-concept Demonstration Report	**5. Report Date** February 2023
	6. Performing Organization Code
7. Author(s) Kyle Garrett, Jiaqi Ma, Bryan Krueger, Aaron Cherney, Ron Schaefer	**8. Performing Organization Report No.**
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Leidos Inc. 11251 Roger Bacon Drive Reston, VA 20190 University of California, Los Angeles Synesis Partners LLC Kittelson & Associates Inc.	**11. Contract or Grant No.** 693JJ319F000345
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Technical Report July 2020 – January 2023
	14. Sponsoring Agency Code HOP

15. Supplementary Notes

Government Task Manager: Kingsley Azubike

16. Abstract

This research investigates the challenges of establishing an automated driving system (ADS)-ready traffic laws and regulations database, as well as access and exchange interfaces to support sharing and consumption of the information within the ADS ecosystem. It also identifies and facilitates the basic interfaces for collaboration among State and local traffic code stakeholders, as well as ADS behavior subject matter experts. This proof-of-concept demonstration report describes the design and implementation of the traffic regulations database framework prototype and proof-of-concept demonstration.

17. Key Words	18. Distribution Statement
Automated Driving Systems (ADS); traffic laws and regulations; uniform vehicle code (UVC); database	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS

AD	automated driving
ADS	automated driving system
API	application programming interface
AV	automated vehicle
CAT	cooperative automated transportation
COU	concept of use
CSV	comma-separated values
C-V2X	cellular vehicle-to-everything
DOT	department of transportation
DSRC	Dedicated Short-Range Communications
FHWA	Federal Highway Administration
HTTP	Hypertext Transfer Protocol
IOO	infrastructure owner-operator
JSON	JavaScript Object Notation
LiDAR	light detection and ranging
MUTCD	Manual on Uniform Traffic Control Devices
ODD	operational design domain
PID	proportional-integral-derivative
RGB	red-green-blue
ROS	Robot Operating System™
RTOR	right-turn-on-red
SME	subject matter expert
TM	traffic manager
USDOT	U.S. Department of Transportation
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
UVC	Uniform Vehicle Code
V2X	vehicle-to-everything

CHAPTER 1. INTRODUCTION

BACKGROUND

The advent of automated driving systems (ADS) and anticipated cooperative ADS will transform the way vehicles interact not only with each other and other travelers, but also with transportation infrastructure, communications infrastructure, information systems, and system management and operations strategies. Infrastructure owner-operators (IOO) and their partner agencies across the country have been grappling with the questions of how ADS will interact with the transportation system—and what they should do to prepare. Uncertainty around the timing of ADS technology development and market penetration has made preparing for this transformation a challenge, underscoring the need for practice-ready information and tools that IOOs can use for planning and deploying resources and policies for the integration of ADS. The National Dialogue on Highway Automation[1] includes a need for a National vision; increased public awareness and support; agency guidance and education; enhanced planning to include probabilistic and scenario-based planning; and data exchange, standardization, and management.

National automation readiness requires a strategic understanding of the context of automated vehicles (AV) and the National transportation infrastructure among all stakeholders. The Federal Highway Administration (FHWA) has been exploring this context through its work in automated vehicles. This exploration includes assessing information and data needs for AV, the National Dialogue on Highway Automation, and other FHWA leadership and working groups. Needs, insights, and opportunities identified through these efforts, as well as coordination with the Cooperative Automated Transportation (CAT) Coalition and other professional and research organizations, are providing essential input for Federal, State, and local initiatives to guide AV implementation. IOOs need insights and tools for planning, developing, and deploying resources as they prepare their organizations, physical assets, and policies to best facilitate and leverage ADS deployment.

Among the key aspects of ADS planning, deployment, and operations, access to data is a critical enabler of safe, efficient, and accessible integration of AVs into the transportation system. On December 7, 2017, the U.S. Department of Transportation (USDOT) hosted the Roundtable on Data for Automated Vehicle Safety.[2] The roundtable demonstrated multimodal alignment around a unified approach to Federal AV policy, and marked the beginning of a new phase of dialogue among public and private-sector stakeholders to accelerate safe deployment of AVs.

The following high-priority use cases for data exchange were identified by roundtable participants:

- Monitoring planned and unplanned work zones.
- Providing real-time road conditions.

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[1] Federal Highway Administration (FHWA), Office of Operations. (n.d.). "National Dialogue on Highway Automation." https://ops.fhwa.dot.gov/automationdialogue/index.htm, last accessed May 11, 2020.

[2] USDOT. 2018. *Roundtable on Data for Automated Vehicle Safety Summary Report*. https://www.transportation.gov/av/data/roundtable-data-automated-vehicle-safety-summary-report, last accessed May 11, 2020.

- Diversifying AV testing scenarios.
- Improving cybersecurity for AVs.
- Improving roadway inventories.
- Developing AV inventories.
- Assessing AV safety features and performance.

A data system related to traffic laws and regulations will facilitate the development of ADS behavior and roadway adaptations that fulfill the vision of safe and effective ADS operations. The ADS Operational Behavior and Traffic Regulation Database framework is, therefore, an important element for realizing effective, robust digital transportation systems for AV integration. It consists of a comprehensive, structured database of traffic regulations that developers could use to set basic programming standards in ADS regarding traffic regulations.

There are challenges to developing ADS. In order to function effectively, ADS must account for the multitude of static and dynamic traffic regulations, which means agencies must provide the regulatory information to ADS and determine how the system would be implemented across the Nation. Traffic regulation information varies among governmental jurisdictions across the Country in format, structure, and implementation. Without common data exchanges, it is almost impossible to develop ADS software that can ensure optimal ADS performance under varying sets of traffic regulations. In short, ADS development needs the traffic regulation database for testing, and for IOOs to ensure well-tuned ADS operational behavior and transportation system safety.

PURPOSE

This research investigates the challenges of establishing an ADS-ready traffic laws and regulations database, and accessing and exchanging requirements to support the sharing and consumption of the information within the ADS ecosystem. It also identifies the basic requirements for collaboration among State and local traffic code stakeholders, as well as ADS behavior subject matter experts (SME).

For consistency and interoperability, it is necessary to develop a comprehensive database framework to support the incorporation of all traffic regulations that enable ADS behavior development and operation. The ultimate goal is to facilitate a traffic regulation specification that supports the development and subsequent operation of traffic with ADS-equipped vehicles. This project involves: a detailed analysis of the ADS readiness of current traffic laws and regulations databases, development of a concept of use (COU), design of a prototype of the traffic laws and regulation database framework, conduction of a simulated proof-of-concept laboratory testbed-simulated demonstration, and development of a model testing plan for a future collaborative implementation of AV integration with the traffic laws and regulations database framework.

The purpose of this proof-of-concept demonstration report is to describe the prototype ADS regulations database design and the prototype database testing. The design is based on the CoU[3] and includes a blockchain database implementation, a traffic regulations data interface, and administrative interface for specifying regulations. The prototype database framework is

[3] FHWA. 2020. *Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information – Concept of Use*, FHWA-HOP-20-041, Washington, DC, FHWA.

implemented with sample regulations data from the Uniform Vehicle Code (UVC) and selected jurisdictions for some operational scenarios, as may be applicable in particular operational design domains, and is fully documented in a project GitHub repository. The prototype demonstration uses the data framework and the CARLA[4] simulation platform to evaluate use of the regulations data interface for two selected scenarios: intersection right-turn-on-red and freeway left-lane use. The testing simulation scripts, videos, and documentation are stored in the project GitHub repository.[5]

The organization of this report is as follows:

Chapter 1 introduces the background and purpose of the research project and this report.

Chapter 2 describes the traffic regulations data framework and implementation.

Chapter 3 describes the proof-of-concept demonstration using the ADS regulations data framework interface and simulations.

[4] CARLA Team 2021. 2021. "CARLA Open-source simulator for autonomous driving research." (website). https://carla.org/, last accessed December 7, 2021.

[5] GitHub. 2021. "ads-traffic-regs." (website). https://github.com/usdot-fhwa-stol/ads-traffic-regs/tree/cherneysp-initial, last accessed December 7, 2021.

CHAPTER 2. TRAFFIC REGULATIONS DATA FRAMEWORK

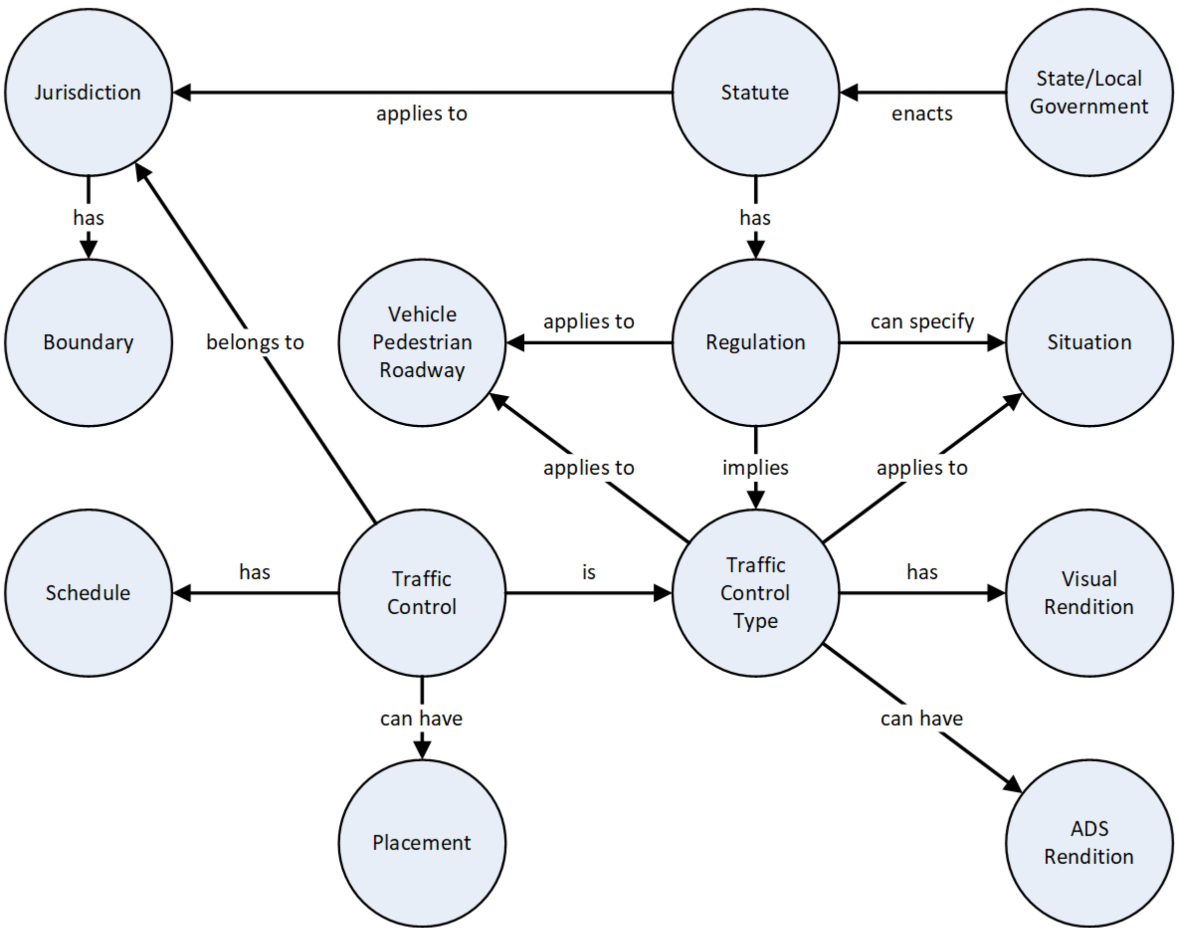
This chapter describes the prototype ADS regulations data framework design and implementation of its database, data interface, and administrative interface.

OBJECTIVE

The objective of the traffic regulations data framework implementation is to fulfill the intent of the CoU for data and interfaces to support providing traffic regulations data to ADS.

REGULATIONS DATA FRAMEWORK

The architectural intent and concept for the regulations data framework are described in the CoU. These concepts are implemented in the demonstration framework. Figure 1, reproduced from the CoU, depicts the system entities and relationships involved in regulating driving behaviors.



Source: FHWA.

Figure 1. Illustration. Automated driving systems regulations data concepts.

Challenges and Limitations on Framework Design

Implementing a traffic regulations framework for use by ADS is challenging due to the nature of traffic regulations, which were created for human drivers, and due to the limitations of automation technologies:

- The human language used in traffic regulations is not in a form that ADS can use without additional development in the machine interpretation of legal texts.
- Standardized interpretation of traffic regulations is limited by the variability in the structure of the regulations text among jurisdictions. The regulations texts do not necessarily use common section numbers or titles.
- Although traffic regulations generally use a consistent set of terms and definitions among jurisdictions, those terms may not readily apply to an ADS development context. Regulations for human interpretation are generally based on descriptions of situations, actions, and maneuvers. Some rules are procedural: "do this, then this." Future work in translation of traffic regulations for ADS applications may need to develop semantic standards for rules and controls.
- As described in the CoU, ADS development environments and simulations do not have "standard" interfaces for traffic rules and controls. Autoware, CARMA, and CARLA, for example, each have their own models. ADS development generally embeds interpretation of rules and controls in the code for specific operational design domains (ODDs).
- Traffic controls generally relate to specific rules within the regulations, but these relationships are not one-to-one. Rules for right turn on a red traffic signal may be confined to a single bounded set of instructions in a traffic code. There may, however, be multiple standard sign configurations associated with a right turn on red, each for a different setting or circumstance.
- Some regulations are interpreted in State-issued driver manuals with more specific guidance. The regulation describes what should or should not be done. The guidance in the manual provides an additional layer of interpretation as to how that regulation can be met.

Design Features and Attributes

From the broad view of its potential use cases, the framework needs to function as a research catalog and a downloadable database. It will provide a structure for capturing traffic regulations from many jurisdictions. The resulting catalog will be most useful as a reference for ADS development and potentially as a local database from which regulations and traffic controls can be accessed for ADS use. Changes to regulations are likely not frequent enough to necessitate real-time updates for vehicles, although changes will be logged and determined from the database.

Similar rules in different jurisdictions need to be linked to the extent that they apply to identical driving situations. Consistency in labels and attributes for driving situations would, at a minimum, enable an ADS to be aware of changes in local regulations for common situations like right turn on red or U-turns. As noted, there is no common reference scheme for traffic regulations, so the approach is to catalog situations within a driving "state space" by maneuver and state variable. Regulations from different jurisdictions readily fall into situations such as, “pass left,” “stop at intersection with a red signal,” and “turn left at intersection with a green signal.”

This approach needs an identified semantic framework to communicate the traffic rules to developers. Creating labels for linking regulations across jurisdictions implies a vocabulary for those situations. Because the regulations apply only to regulated roadway operations, however, the constraints on that state space implies a finite set of potential regulated states and sensed conditions.

The instructions provided by regulations may vary even for those situations that are common to a group of jurisdictions. The intent of the framework, however, is to be able to identify cases where the regulations may vary, and not to parse the variations within those regulations. Some regulations are procedural, such as stopping at a red traffic signal. The details in those procedural descriptions may nonetheless vary among jurisdictions. The framework will capture the various regulations for each situation, but not directly parse them to identify specific differences.

Traffic regulations need to be identified with the applicable traffic controls—markings and signs, and traffic signal indications—as part of describing the “state space” to be expected within a jurisdiction. The ADS needs to be able to identify the applicable controls from its sensors and detection systems. The regulations framework then needs to catalog applicable control types for jurisdictions. There may be future value in cataloging the specific locations of deployed controls, so that control detections can be confirmed with the catalogued control geolocations, or used as a backup to on-board detection.

Current ADS implementations appear to be algorithmic, but not parameterized. Rules for operating within an ODD are captured within the algorithms used in that ODD, but do not appear to be parameterized such that a common set of rules (algorithms) could be applied to multiple ODDs. As such, it does not appear that the regulations framework needs to provide an explicit parameterized procedural breakdown of the rules within particular regulations. This further implies that the guidance in driver manuals does not need to be included in the framework. Such guidance is not regulatory and may not apply to ADS. However, an ADS might violate human driver expectations (e.g., for following distance) if guidance for human drivers is not applied.

The quantity of jurisdictions in the United States and the variability of the traffic regulations among them preclude populating the demonstration regulations framework with all local regulations. Automated collection and ingestion of regulations might be available as a third-party service, at least for those regulations that are available in digital formats. In the meantime, the initial cataloging of regulations will need human interpretation. A complete National ingest and update may warrant investigation of natural language processing and machine learning techniques.

Blockchain Implementation

The prototype implementation of the ADS regulations data framework is based on blockchain technology. Managing records of jurisdictional regulations is inherently public and distributed. The integrity and authority of the regulations must be protected. A blockchain’s published and distributed ledger of records lends itself well to this situation.

A blockchain peer-to-peer network enables jurisdictions to both assert and attach authority to and verify the integrity of published traffic regulations. The network further enables jurisdictions to establish publishing reciprocity, such that jurisdictions can recognize and vouch for the authority of each other's published regulations.

Regulations published using blockchain methods additionally maintain their change history. Each regulation update is identified by a mathematically immutable identifier created as part of that update. ADS can independently apply the same algorithm to verify that received regulations are authoritative.

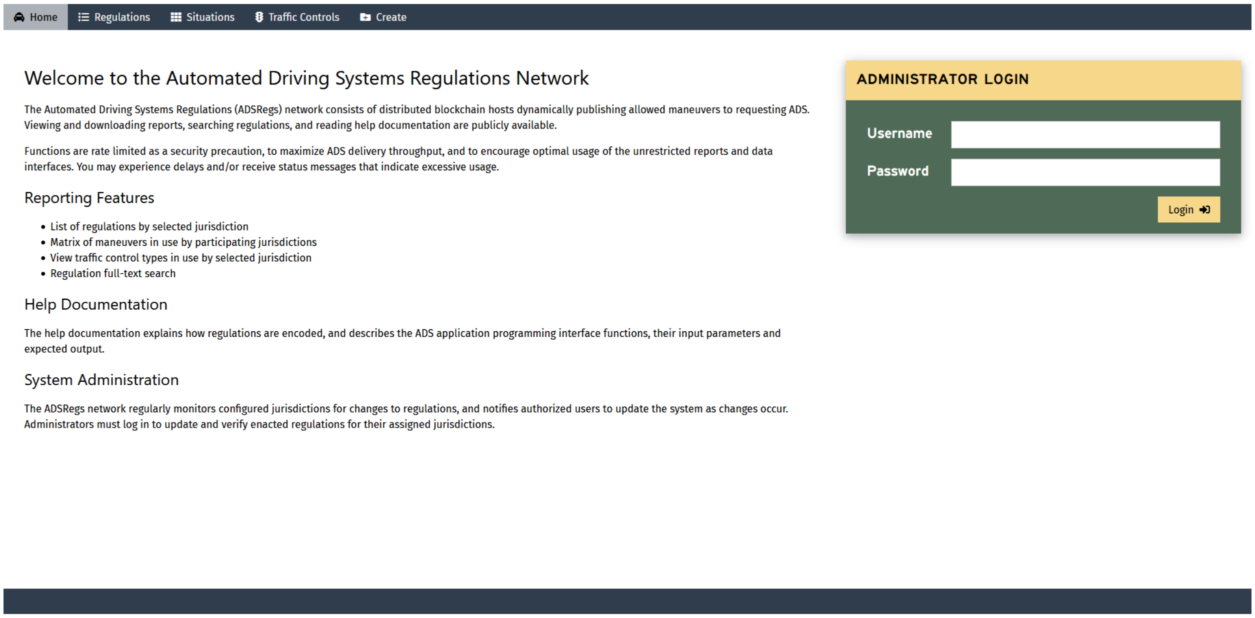
The distributed nature of the blockchain network ensures that ADS-equipped vehicles requesting regulations data for a particular jurisdiction receive prompt and authoritative responses from nearby blockchain hosts, even if the request is for a remote jurisdiction. This ensures network responsiveness while reducing the burden on any one host.

PROTOTYPE USER INTERFACE

An ADS traffic regulations data framework requires interfaces for administratively capturing the regulations data and for providing data to end users and systems. As shown in figure 2, a fully developed interface requires user login such that that the system can distinguish between administrative and end-user accounts. The prototype framework acknowledges this distinction by showing a login panel, but has not implemented the underlying account management services. Enforcing those roles and implementing account management is not needed for the prototype demonstration and would unnecessarily complicate the development. All users of the prototype have access to administrative and end-user functions.

Administrative User Interface

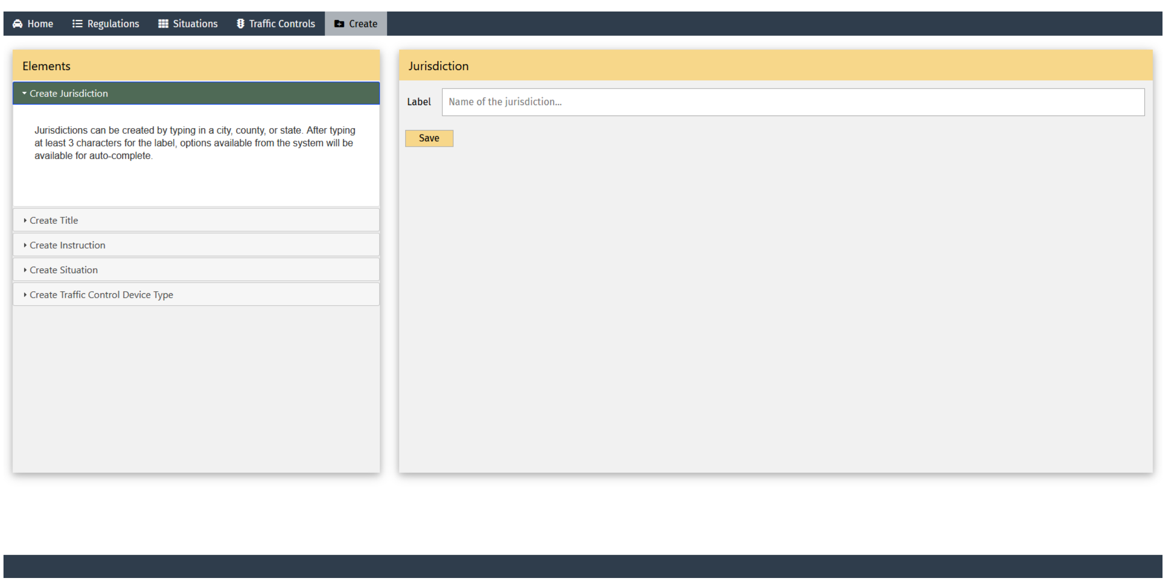
In concept, the administrative user has access to create and edit traffic regulation data records, whereas the end user can view, but not edit. The administrative role may eventually involve a more sophisticated process to create, validate, and approve the records. A real world implementation may require a minimum of two independent reviewers would then be needed to ensure records quality. Creators would not be able to validate new or modified records, and validators would not be able to approve those records.



Source: FHWA.

Figure 2. Screen Capture. Automated driving systems regulations user interface home screen and login.

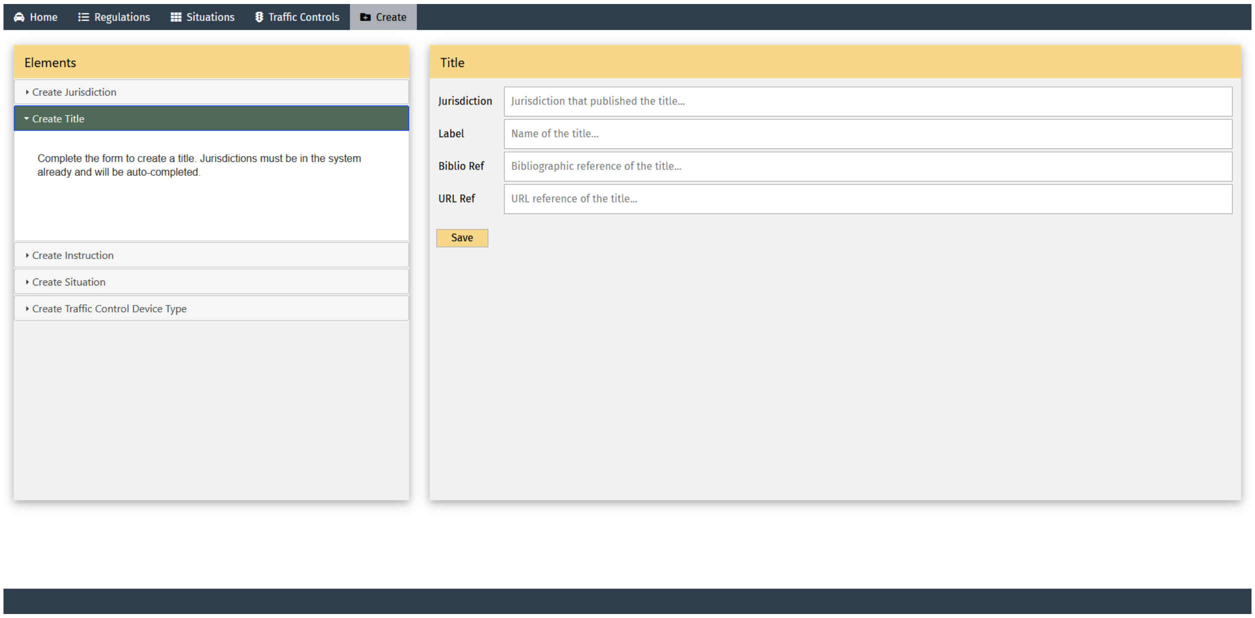
An administrative user adds new regulation records by selecting the "Create" item from the application top menu, as shown in figure 3. The application then displays a menu of data "Elements" in the left-hand panel. The administrative user then works down the list of elements to create records for the regulations applicable to their jurisdiction. The system contains records of jurisdictions for which boundaries are available, and the administrative user selects one for which to create records of traffic regulations.



Source: FHWA.

Figure 3. Screen Capture. Automated driving systems regulations user interface for addition of a new jurisdiction.

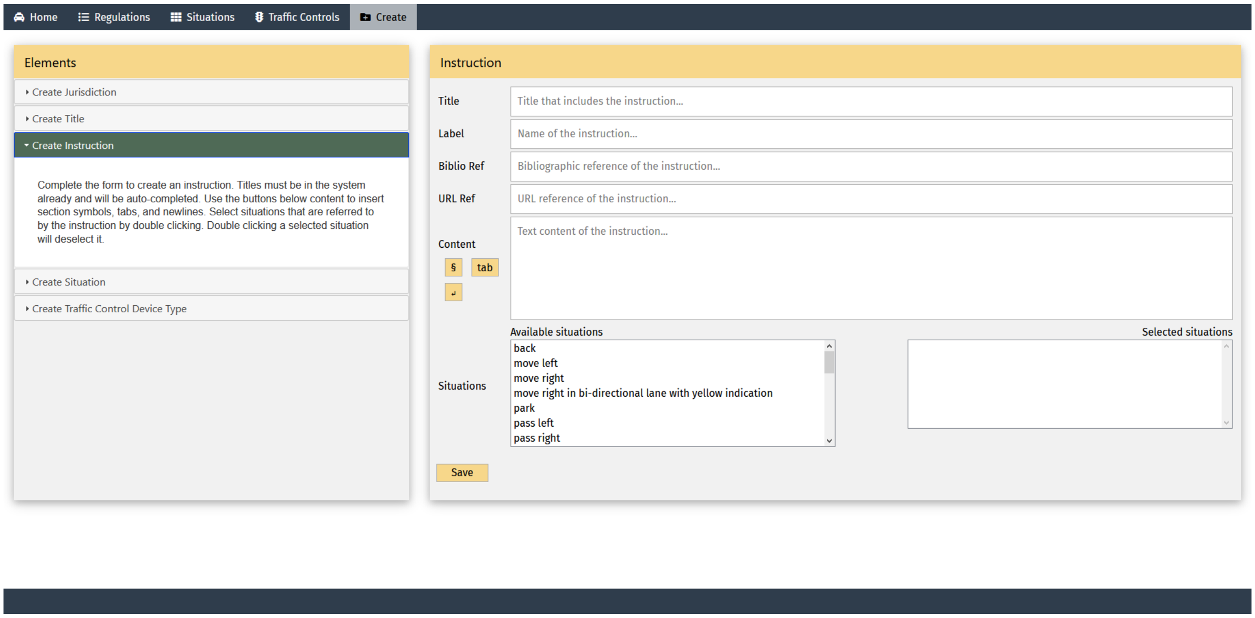
The “Title” data element describes the collective body of traffic regulations for which the records are being created, as shown in figure 4. It provides data entry for the appropriate source bibliographic and internet Uniform Resource Locator (URL) references.



Source: FHWA.

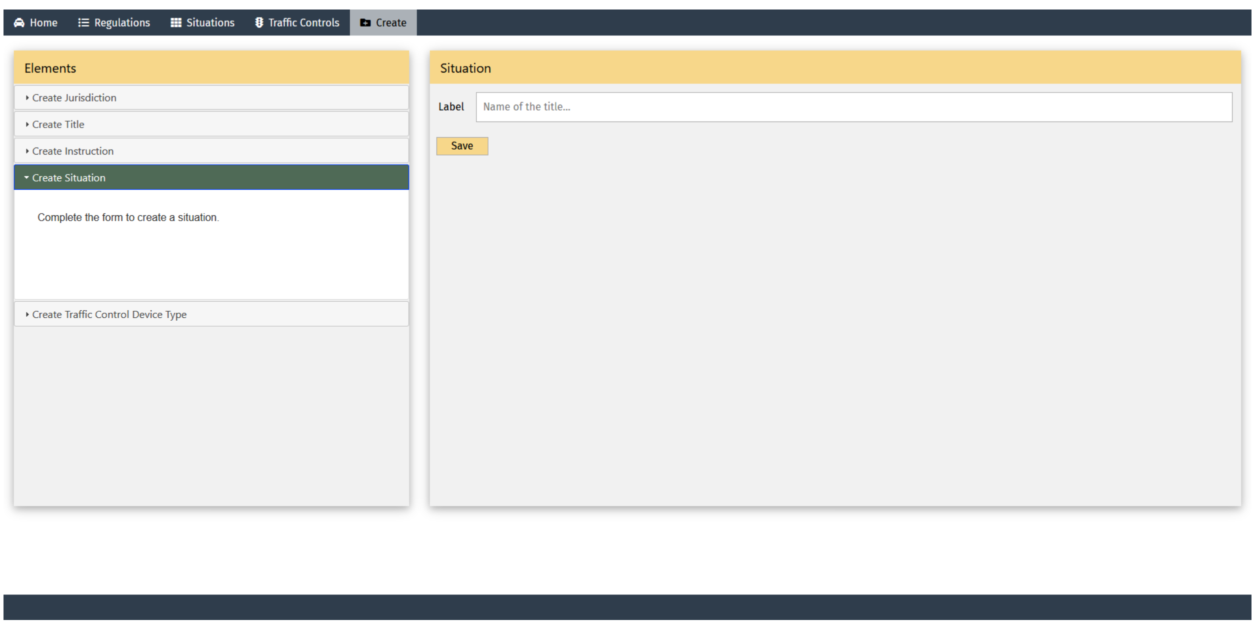
Figure 4. Screen Capture. Automated driving systems regulations user interface for addition of regulatory references.

The “Instruction” element, shown in figure 5, captures the specific text of the traffic regulation from the reference title. An “instruction” will generally be a self-contained section of text, such that it does not depend on the text of another section to be understood or applied to a driving situation. Each text is linked to a list of one or more such situations. New “Situation” elements can be added for the jurisdiction as shown in figure 6.



Source: FHWA.

Figure 5. Screen Capture. Automated driving systems regulations user interface for addition of situational instructions.

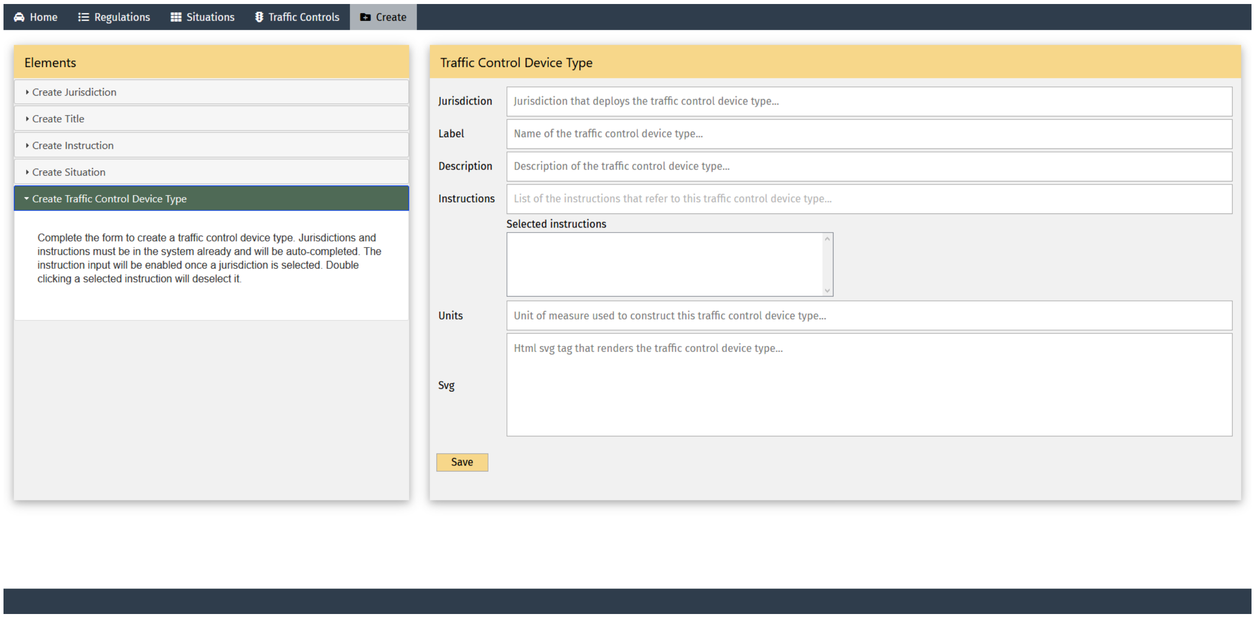


Source: FHWA.

Figure 6. Screen Capture. Automated driving systems regulations user interface for addition of situations.

Traffic control types link the traffic regulations to those devices—signs, signals, and pavement markings—that are deployed to roadways to indicate that those controls (and the regulations behind them) are in force at particular locations. As shown in figure 7, the "Traffic Control Device Type" elements describe the types of controls that may be encountered by a driver or ADS within a jurisdiction. Traffic control devices will be defined by the Manual on Uniform

Traffic Control Devices[6] (MUTCD) or the jurisdictional equivalent as specified in its traffic regulations.



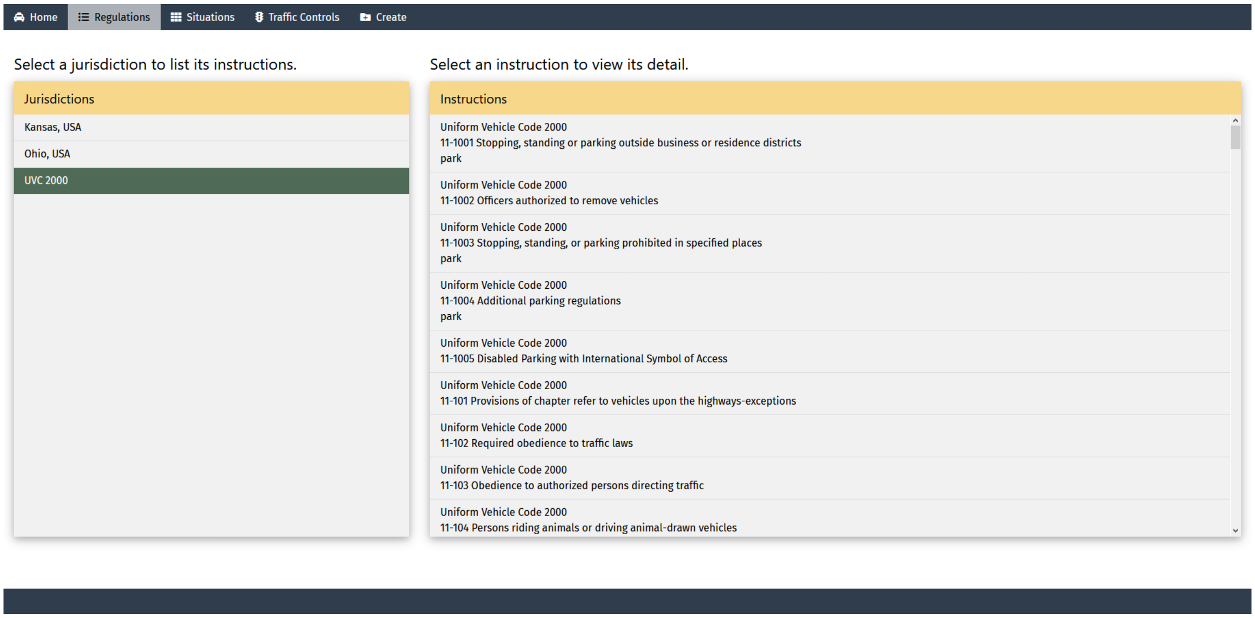
Source: FHWA.

Figure 7. Screen Capture. Automated driving systems regulations user interface for addition of traffic control device types.

End-user Interface

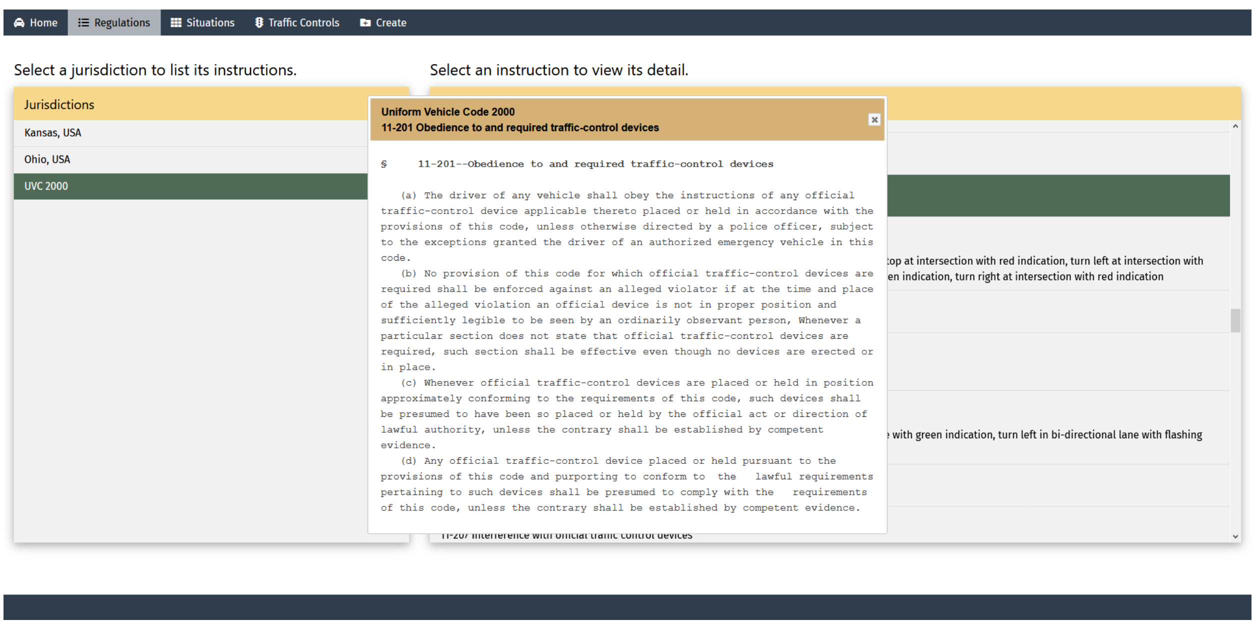
The end-user interface enables those users to view the ADS traffic regulations data captured within the framework. As shown in figure 8, selecting the "Regulations" item on the top menu presents a list of jurisdictions for which regulations have been captured in the data framework. Selecting a jurisdiction from the left-hand panel then displays a list of regulatory system "instructions" in the right-hand panel. Selecting a particular instruction displays the text of that instruction in an overlaying panel, as shown in figure 9. The overlay panel can be closed with the "x" button to select a different instruction.

[6] FHWA. 2012. *Manual on Uniform Traffic Control Devices for Streets and Highways*, Washington, DC: FHWA.



Source: FHWA.

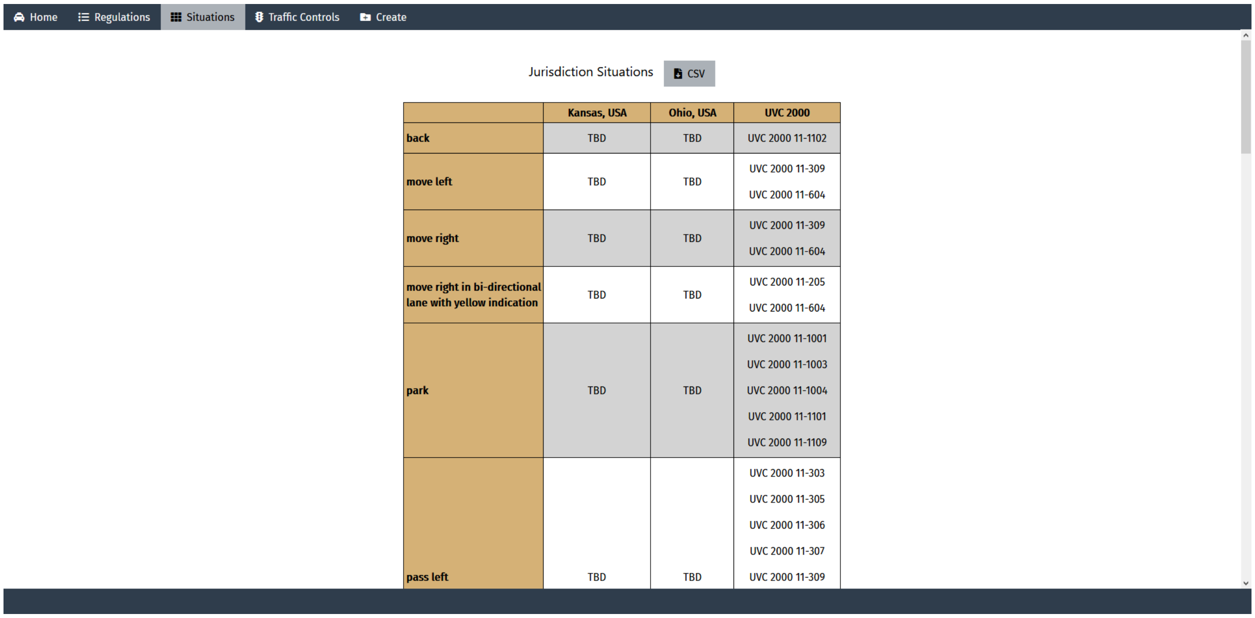
Figure 8. Screen Capture. Automated driving systems regulations user interface displaying jurisdictions and instructions (sections).



Source: FHWA.

Figure 9. Screen Capture. Automated driving systems regulations user interface displaying the text of regulations.

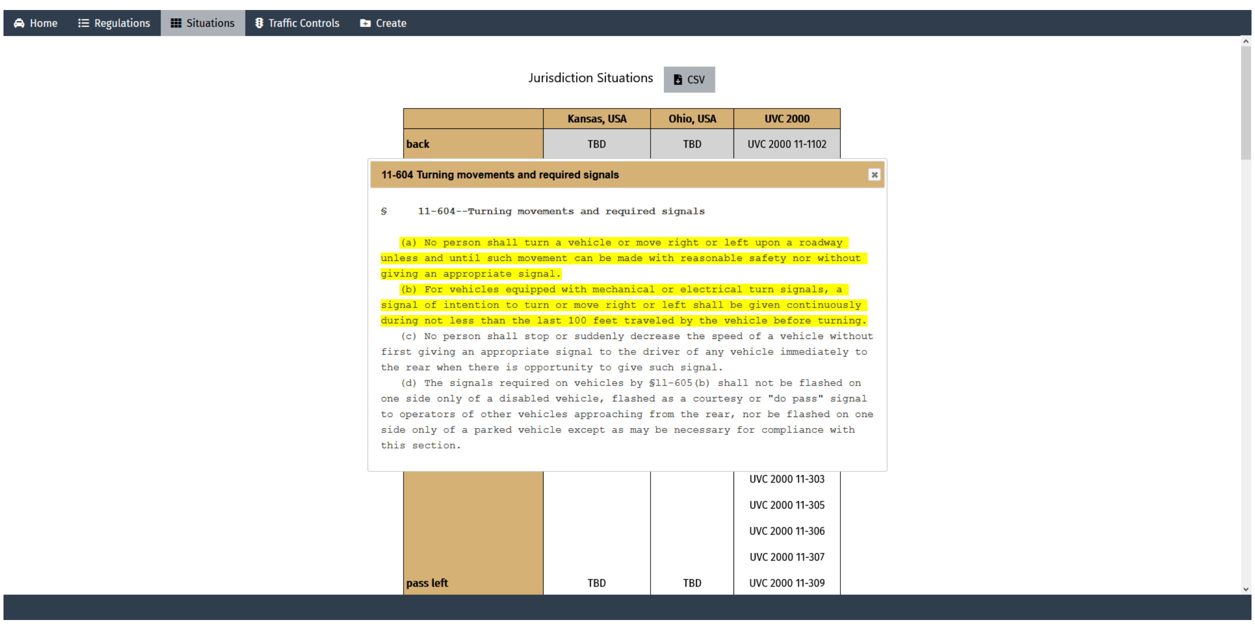
Situations to which regulations may apply are displayed using the “Situations” item in the top menu. The results, as shown in figure 10, are presented in a table listing situations defined in the system with the sections of regulations (instructions) that apply to each situation for each jurisdiction. Situations for which instructions have not been identified in the system are indicated by "TBD" ("to be determined"). The button labeled "CSV" ("comma-separated values") initiates a download of the table in CSV format.



Source: FHWA.

Figure 10. Screen Capture. Automated driving systems regulations user interface displaying the association of situations with jurisdictions.

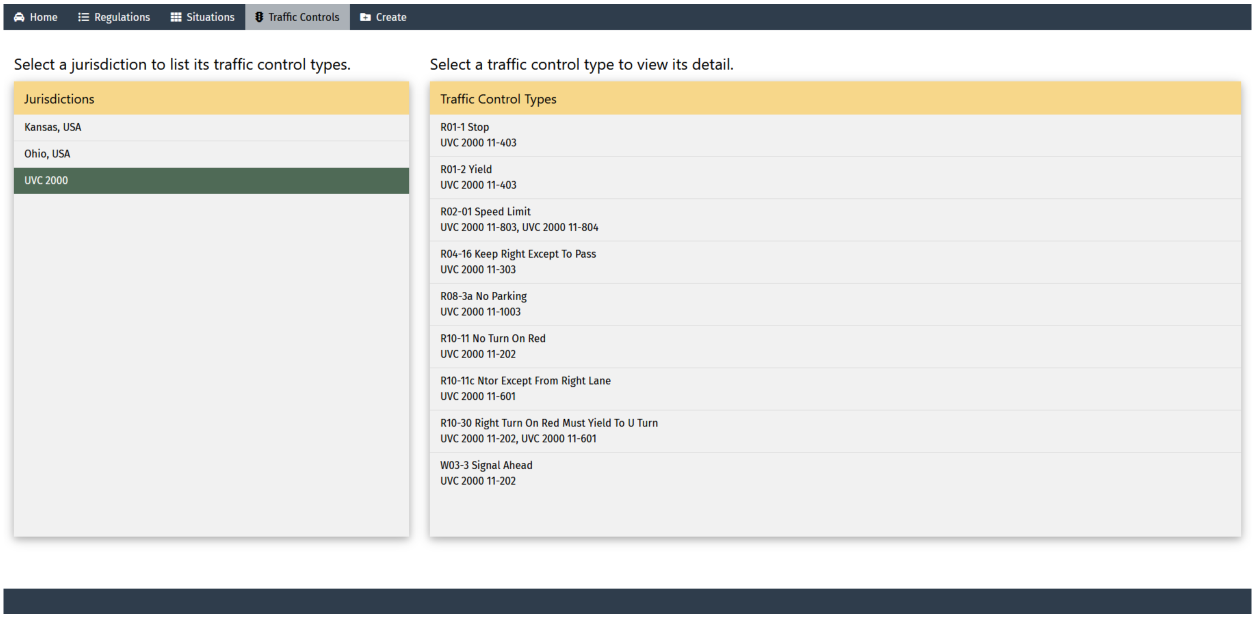
Selecting a particular instruction in the table opens an overlay of the text of that instruction, as shown in figure 11.



Source: FHWA.

Figure 11. Screen Capture. Automated driving systems regulations user interface displaying the text of regulations for a particular jurisdiction and situation.

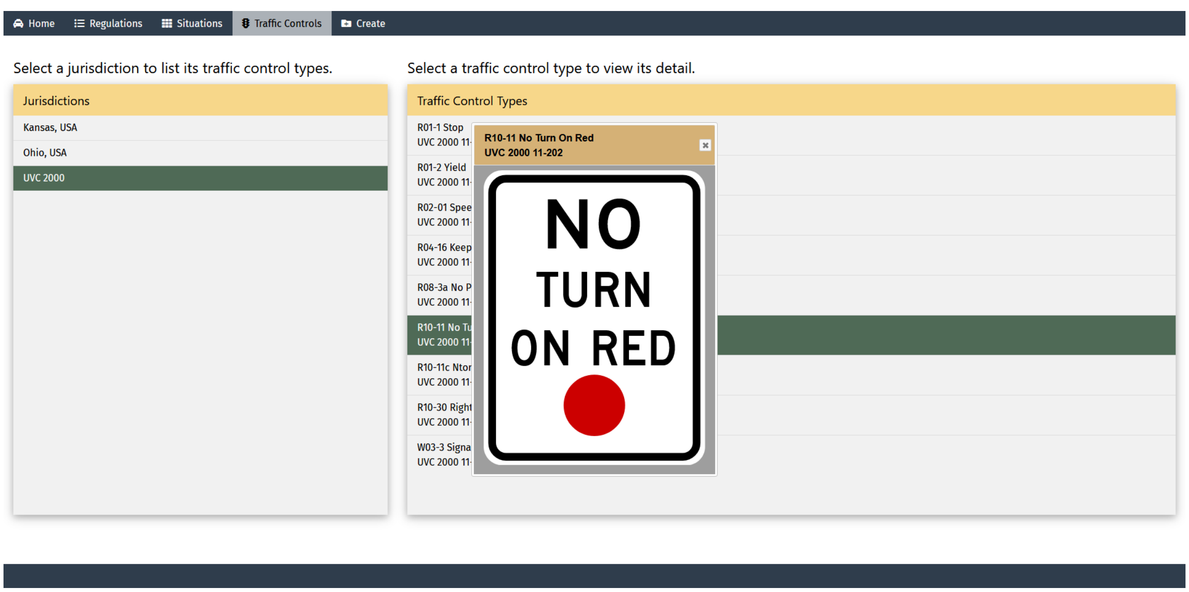
Selecting the "Traffic Controls" item in the top menu displays the list of jurisdictions in the left-hand panel, as shown in figure 12. Selecting a jurisdiction provides a list of traffic control types associated with that jurisdiction in the right-hand panel.



Source: FHWA.

Figure 12. Screen Capture. Automated driving systems regulations user interface displaying the association of jurisdictions and traffic control types.

Selecting a traffic control type displays an image of the associated traffic control device, as shown in figure 13.



Source: FHWA.

Figure 13. Screen Capture. Automated driving systems regulations user interface displaying a traffic control image associated with a jurisdiction.

PROTOTYPE APPLICATION PROGRAMMING INTERFACE

The ADS regulations data framework is accessed using three application programming interfaces: jurisdiction, boundaries, and situations. The interfaces are accessed through Hypertext Transport Protocol (HTTP) and post specifically named parameters to a URL endpoint. Responses are JavaScript Object Notation (JSON) formatted text.

The jurisdiction interface Uniform Resource Identifier (URI) endpoint is api/jurisdiction, and its parameters are "lat" and "lon," to specify a latitude and longitude point of interest, such as the vehicle's current location. Latitude and longitude are in decimal degrees. The response is a list of unique identifiers and names for geographic boundaries included in the jurisdiction encompassing the requested location.

The boundaries interface URI endpoint is api/boundaries, and its parameter is "id." The "id" is the unique identifier for a jurisdiction determined by the jurisdiction interface. The response contains the geo-coordinates (in decimal degrees) of a bounding box for the requested boundary, plus the list of geo-coordinates that define the region.

The situations interface URI endpoint is api/situations, and its parameter is "id". In this case, the "id" is also the unique identifier for a jurisdiction determined by the jurisdiction interface. The response is a list of valid situations active for the given jurisdiction.

PROTOTYPE FRAMEWORK REPOSITORY

The prototype ADS traffic regulations data framework is maintained in a GitHub repository at https://github.com/usdot-fhwa-stol/ads-traffic-regs/tree/cherneysp-initial.

CHAPTER 3. PROOF-OF-CONCEPT DEMONSTRATION

This chapter describes a proof-of-concept demonstration of the operations of an automated driving system (ADS)-equipped vehicle with connection to the traffic regulations framework prototype presented in chapter 2.

OBJECTIVE

The objective of the demonstration is to show how traffic laws and regulations, as stored in the traffic regulations framework, can be processed by a typical automated driving system (ADS) platform and subsequently affect the operational behavior of ADS-equipped vehicles. The demonstration is conducted in an automated driving (AD) simulator equipped with additional development modules that help ADS-equipped vehicles process traffic regulations information for vehicle behavior planning and control. Specifically, the tasks of the demonstration are as follows:

- Understand ADS vehicle behavior under different laws and regulations.
- Test the traffic regulations database prototype in a simulated environment with high-resolution interactions between ADS-equipped vehicles, roadway infrastructure, and general traffic.
- Collect data and enhance the understanding and testing of ADS systems, particularly the performance of various components of ADS software under different regulations, traffic, and infrastructure environments.
- Create demonstration videos using a 3D animation engine.

SIMULATION PLATFORM – CARLA

CARLA is an open-source simulation software designed specifically for automated driving systems (ADS). It is frequently referred to as an AD simulator. The platform allows for extensive and detailed customization of the environment, actors (any created entity), and map generation, among others. CARLA is grounded on Unreal Engine to run the simulation and uses the OpenDRIVE standard to define roads and urban settings. Control over the simulation is granted through an application programming interface (API) handled in Python® and C++.

The CARLA simulator has a scalable client-server architecture, as illustrated in figure 14. The server is responsible for everything related to the simulation itself, such as sensor rendering, computational physics, and updates on the world-state and its actors. The client side consists of a sum of client modules controlling the logic of actors on the scenes and setting world conditions. This is achieved by leveraging the CARLA API (in Python or C++) layer that mediates between the server and the client and is constantly evolving to provide new functionalities.

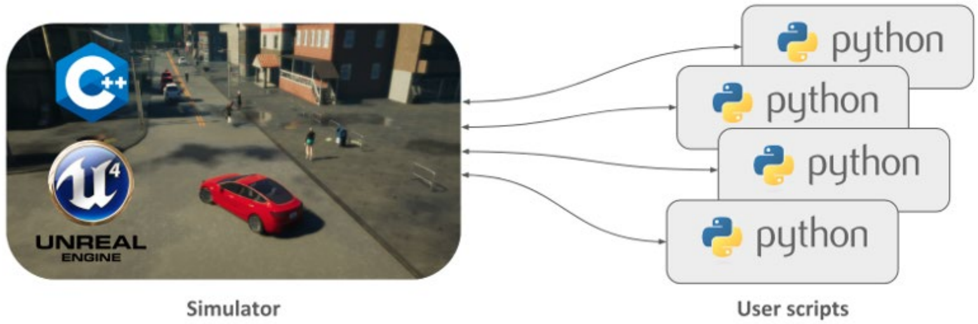


Figure 14. Illustration. CARLA Core Simulator and Python® application programming interfaces.

Key features and elements of CARLA include the following:

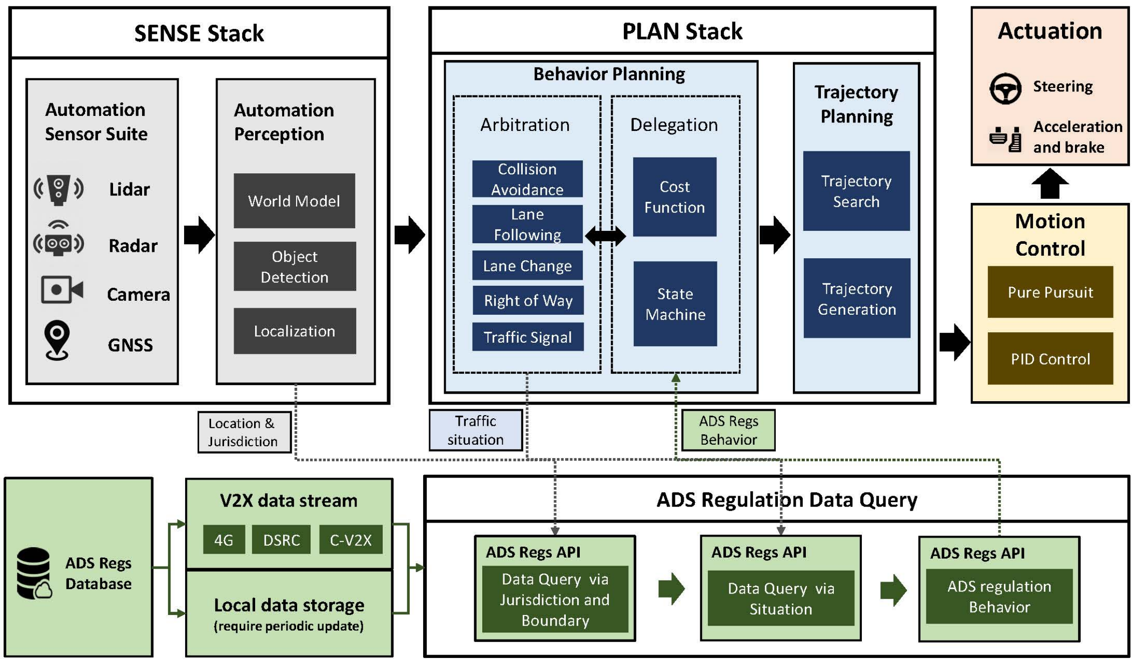
- **Traffic manager.** A built-in system that models the roadway environment. It acts as a conductor to recreate environments with realistic behaviors.
- **Sensors.** Vehicles rely on sensors to dispense information about their surroundings. In CARLA, sensors are a specific kind of actor attached to the vehicle, and the data they receive can be both retrieved and stored to ease the process. CARLA includes several sensors to ease this process, such as red-green-blue (RGB) image, semantic, and depth cameras, as well as radar, LiDAR, and a few specific to CARLA. Each sensor in the suite has customizable parameters and locations. Also, CARLA provides measurements associated with the state of the environment, such as vehicle location, velocity, acceleration, traffic light state, lane locations, and speed limits at any location. These measurements are essential to modeling realistic behavior.
- **Robot Operating System (ROS™) Bridge and Autoware Implementation.** As a matter of universalization, the CARLA project ties knots and works for the integration of the simulator within other learning environments.
- **Open assets.** CARLA facilitates different maps for highway and urban settings with control over weather conditions, and a blueprint library with a wide set of actors to use. These elements can be customized and new ones can be generated by the user.
- **Scenario runner.** To ease the learning process for vehicles, CARLA provides a series of routes describing different situations to iterate on.

The traffic laws and regulations can be incorporated as surrounding traffic environments through Python APIs and sent to the subject ADS vehicles directly. Then, the ADS planning and control modules will take this information as input. This inupt being a part of the dynamic world model that has been created by the environment sensing and perceiving modules, to plan and implement the maneuvers that meet the requirements prescribed by traffic laws and regulations.

SIMULATION TESTING WORKFLOW AND INTERFACES

In this project, we aim to connect the traffic laws and regulations database with a standard automated driving platform to serve as a proof-of-concept. The upper part of figure 15 shows a standard ADS software platform, including four stacks: sense, plan, control, and actuation. The

ADS Regulations Database can be local on the vehicle storage (downloaded before the trip) and/or accessed in real time through vehicular communications (e.g., when the vehicle enters a new geographic area). The vehicle SENSE Stack generates the location of the vehicle and then extracts the most relevant laws and regulations stored in the ADS regulations database. The queries from the database are based on vehicle jurisdictions and boundaries and the vehicle's driving situation. The database then generates allowed ADS regulation-related behavior. This behavior output will feed to the behavior planning module of the PLAN Stack and this information will integrate into the overall behavior planning software module. Therefore, the generated ADS behavior will be constrained by the relevant ADS regulations.



Source: FHWA.
ADS = automated driving system. API = application programming interface. C-V2X = cellular vehicle-to-everything. DSRC = dedicated short-range communications. GNSS = Global Navigation Satellite System. PID = proportional-integral-derivative. V2X = vehicle-to-everything. 4G = fourth-generation broadband cellular network technology.

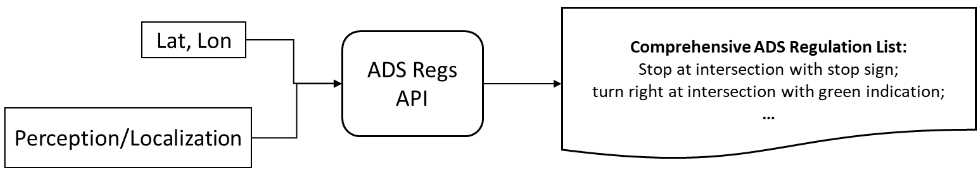
Figure 15. Illustration. Automated driving system latform architecture with traffic regulations database.

The workflow for architecture implementation includes the following five steps or components and will be discussed in subsequent subsections:

- Access ADS regulation data by location (i.e., coordinates, outputs of perception/localization).
- Maintain a legal regulation list for the current location (i.e., temporary location-specific list).
- Vectorize the ADS regulations.
- Vectorize the vehicle's intention.
- Determine the behavior's legality and replan behavior if needed.

Access Regulation Data

The first step in the workflow is to access and query ADS regulation data by location using a combination of global positioning system (GPS) coordinates and outputs of the perception and localization software module of ADS, as illustrated in figure 16. In our CARLA simulation example, we map some real-world coordinates to our simulated world in the database for demonstration purposes. Through the ADS regulations API, the vehicle retrieves a comprehensive list of ADS regulations relevant to the current location. Some examples include "Stop at intersection with stop sign" and "Turn right at the intersection with the green indication." Some of these regulations are standard, like the former example, and regular ADS platform can already handle those regulations. However, the latter regulation is location-specific, and the ADS platform will need to comprehend this information in its trajectory planning.

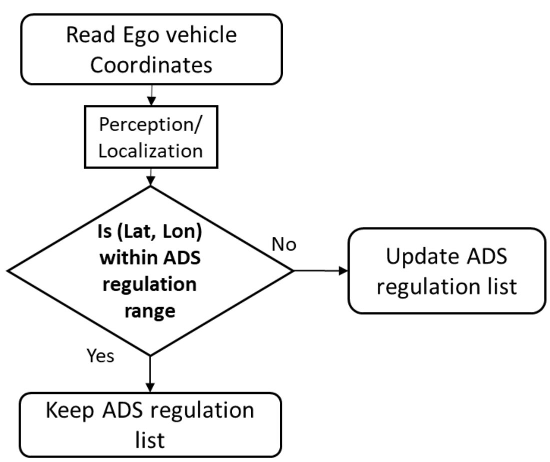


Source: FHWA.
ADS = automated driving system. API = application programming interface. Lat = latitude. Lon = longitude.

Figure 16. Diagram. Workflow for accessing regulations data.

Maintain a Regulation List for the Current Location

As shown in figure 17, the vehicle constantly queries regulation information relevant to the current location and updates the regulation list in the temporary memory if some regulations are not applicable anymore; e.g., outside the applicable range. While this update does not need to operate at the regular control update frequency (e.g., 0.1 seconds), this list needs to be updated every few seconds to ensure the latest regulation lists are used in ADS behavior planning.

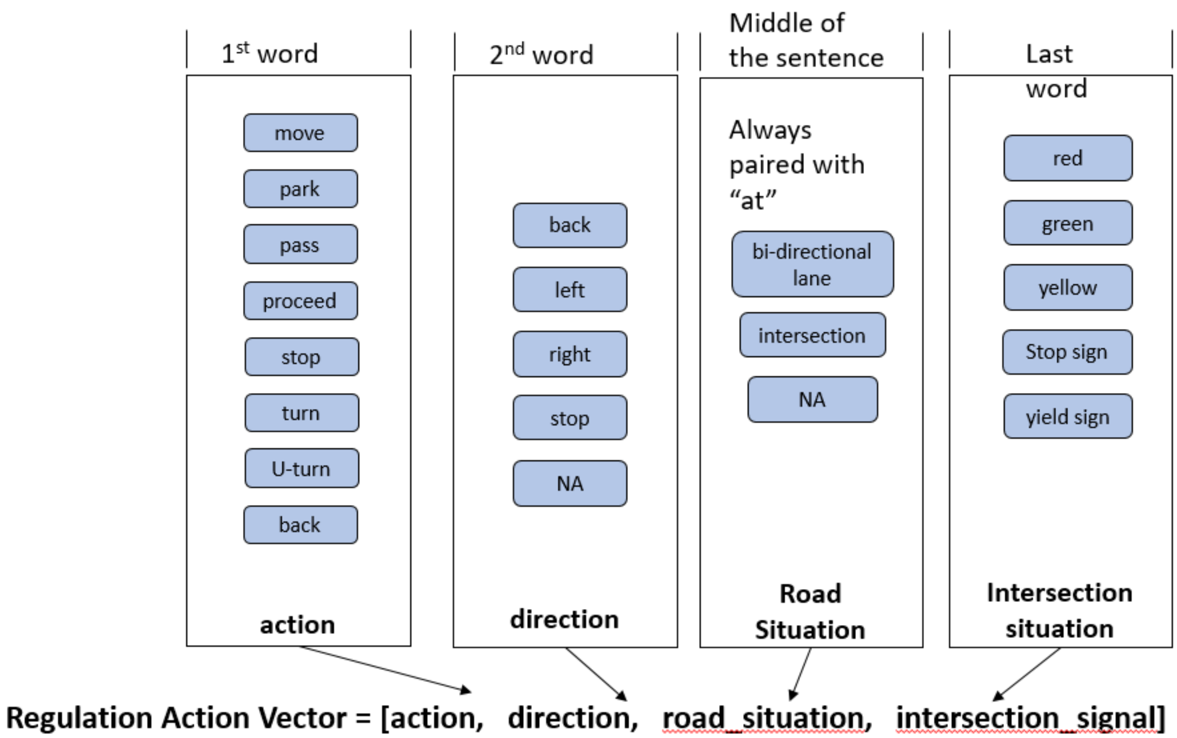


Source: FHWA.
ADS = automated driving system. Lat = latitude. Lon = longitude.

Figure 17. Diagram. Worflow for maintaining legal regulation list in automated driving systems for current vehicle location.

Generate Regulation Action Vector for Automated Driving System Regulations

The third component is to use the extracted list of regulations to generate the ADS Regulation Action Vector, as shown in figure 18. All the regulation languages in the ADS regs database, originally from the UVC, share a similar language structure: action, direction, road situation, and intersection situation. These four components are then added together to generate the Regulation Action Vector. In this demonstration, this Regulation Action Vector is compared to the ADS-equipped vehicle intent vector to determine if the ADS behavior is legal.

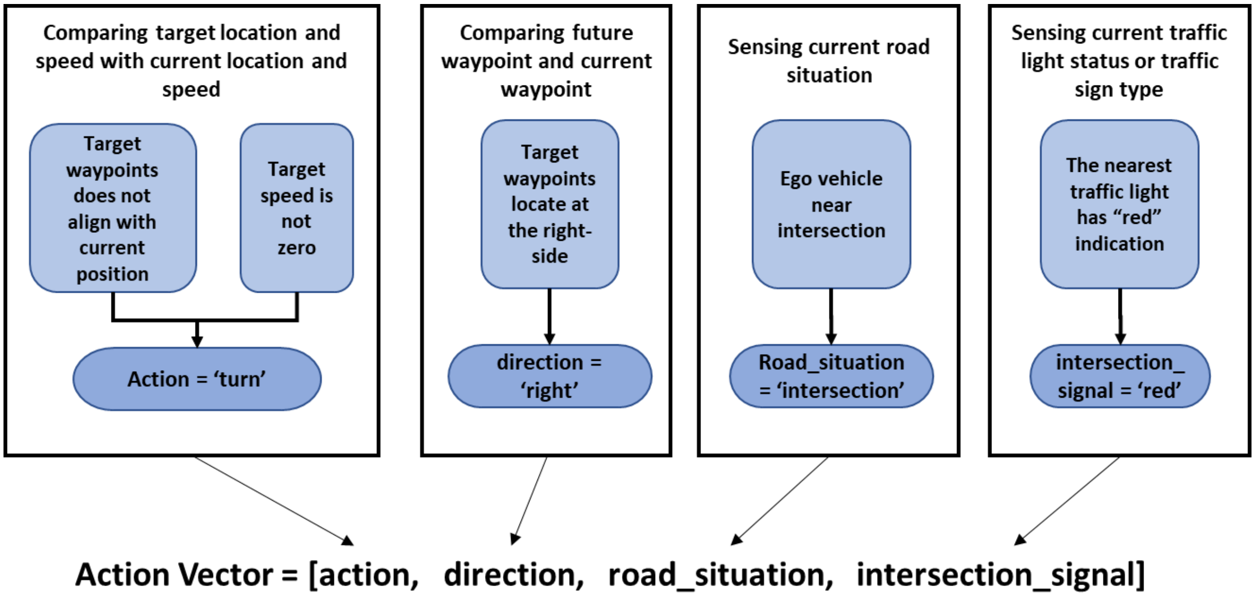


Source: FHWA.

Figure 18. Diagram. Generate regulation action vector for automated driving system regulations.

Vectorize the Vehicle's Intention as Intention Action Vector

The fourth step is to summarize the vehicle's current intention (i.e., intended behavior from the baseline behavior planning module if the traffic regulations are not considered) into an Intention Action Vector. Generally, the behavior includes information such as future waypoints or target trajectories (which include future locations and speeds). As shown in figure 19, a program is created to turn the planned waypoints and trajectories into the Intention Action Vector, which will then be compared with the Regulation Action Vector.

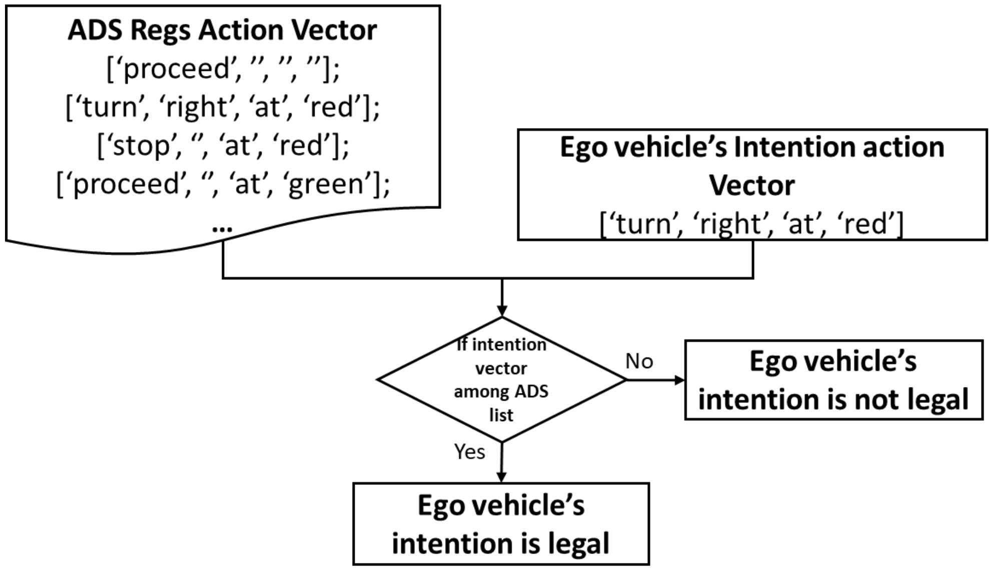


Source: FHWA.

Figure 19. Diagram. Vectorize the vehicle's intention as an intention action vector.

Determine the Vehicle Behavior's Legality

The last step of the workflow is to compare two vectors, (ADS Regulation Action Vector and Intention Action Vector), as shown in figure 20. If there is a match (i.e., the Intention Vector is in the set of Regulation Action Vectors), the intention is legal. If not, the intention is illegal. If illegal, the behavior or trajectory planner will re-plan the behavior and trajectory. This can be done in multiple ways. For example, the PLAN Stack can generate many multiple candidates for the next behavior and trajectory and compare each of the candidates to the ADS Regulation Action Vector to determine if the plan is legal. The final determination of behavior and trajectory can be a combination of legality and efficiency, safety, and other performance measures. In this process, the illegal behavior will be significantly punished and not selected by the ADS Plan Stack. While this or other methods can be used for future real-world deployment, we use this method for simplicity and clarity in this proof-of-concept demonstration.



Source: FHWA.
ADS = automated driving system. Ego = the vehicle being automated.

Figure 20. Diagram. Workflow for determining the vehicle behavior’s legality.

TESTING SCENARIOS AND RESULTS

A proof-of-concept demonstration of the traffic regulations database prototype is demonstrated with the above-mentioned simulation-based testing platform. The demonstration is performed under two different environments: freeways and urban streets with signalized intersections, for the purpose of testing two different traffic regulations, i.e., freeway left-lane use and right-turn-on-red (RTOR), respectively. In each of the simulations, the proof-of-concept ADS software in the simulation is designed to operate under the specific roadway types with different operational rules. For example, during the urban street testing, the ADS understands the traffic lights and can act according to the light indications. This means that the ADS are designed to operate under specific components of the operational design domain (ODD) in each simulation. Note that, in this study, the traffic regulations are not a pre-defined ODD component and the ADS considers the regulations information as a component of the dynamic world model, from which the ADS will generate planned behavior and trajectories.

Demonstration Workflow

In each simulation, the overall workflow is described below:

- The simulated environment contains both ADS-equipped vehicles and simulated human-driven vehicles.
- ADS-equipped vehicles are controlled by CARLA AV-agent, a client-side ADS platform.
- Background traffic is generated by the traffic manager (TM) to simulate the existence of other vehicles. It is also associated with a dedicated client in CARLA.
- The simulation is running in the synchronous mode in which the world simulates one time-step after both clients (i.e., AV client and TM client) update.

Specifically, the workflow for each of the ADS-equipped vehicle agents in the simulation is described as below:

- The sensor data are simulated by CARLA.
- In the localization phase, all data will be transformed to CARLA world coordinates.
- All path planning functions are implemented in the “local planner” class that is associated with individual ADS-equipped vehicle.
- ADS controls are deployed by a proportional-integral-derivative (PID) controller that adjusts the current control values according to the ideal value provided by the “local planner”.
- Interfacing with traffic regulation database:
    - The CARLA ADS-equipped vehicle agent is connected to the prototype database developed by Synesis Partners.
    - The traffic regulation data will be extracted and converted for use by the ADS-equipped vehicle agent.
    - The traffic regulations will be reflected and implemented in the local planner/path planning module (i.e., the algorithm will penalize path/trajectories that violate local traffic regulations).

Please refer to chapter 2 for descriptions of the interfaces between the traffic regulations database and the simulated ADS platform.

AUTOMATED DRIVING SYSTEM TESTING RESULTS

Simulation results and discussions are presented in this section for each of the two simulation scenarios.

Intersection Right Turn on Red

The first scenario concerns traffic regulations at signalized intersections on urban streets. The focus being whether RTOR is allowed at intersections when the traffic light is red. The specific details of the scenario are as follows:

- Four-way intersection environment.
- Right-lane traffic is or is not allowed to turn right on the red light in safe conditions.
- This may result in different AV intersection approach and departure behaviors.
- Traffic stream contains both automated vehicles and human-driven vehicles.

Figure 21 illustrates the simulation demonstration and results. Figure 21(a) shows an ADS-equipped vehicle is approaching the signalized intersection with all traffic light indications in red. In this figure, the scenario shows that the ADS comprehends that RTOR is not allowed at this intersection. The X marks in the figure are waypoints along the vehicle's planned future trajectory. Even though the vehicle intends to cross the stop bar and turn right, the active regulation of no RTOR makes the ADS replan the trajectory and it can be seen from the figure that the last waypoint ends at the stop bar, indicating that the vehicle has planned a trajectory to stop at the stop bar. In figure 21(b), which is the same simulation under the same scenario of RTOR not allowed, the vehicle waits until the green indication to replan the trajectory to make a right turn and complete its intention. In figure 21(c), which is under a different scenario of RTOR allowed, even when the red traffic light indication is on, the vehicle stops at the intersection briefly for safety purposes (the default logic of the simulated baseline ADS platform). The vehicle then continues the right-turn maneuver by following the originally planned trajectory, with the understanding of RTOR allowed when the vehicle was approaching the intersection with the red indication on.

(a) Vehicle approaching and stopping at red light.

(b) Vehicle starting new waypoints until green.

(c) Vehicle starting new waypoints with red.

Source: FHWA.

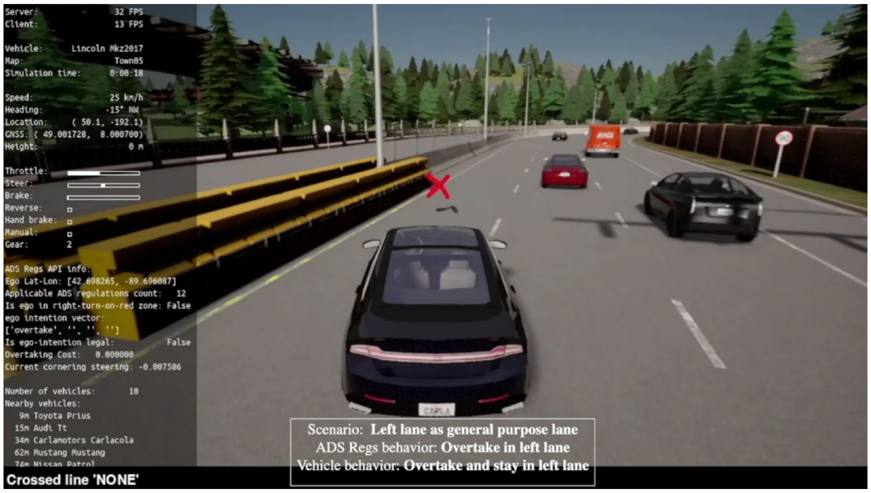
Figure 21. Illustration. Intersection right-turn-on-red demonstration.

Freeway Left Lane Use

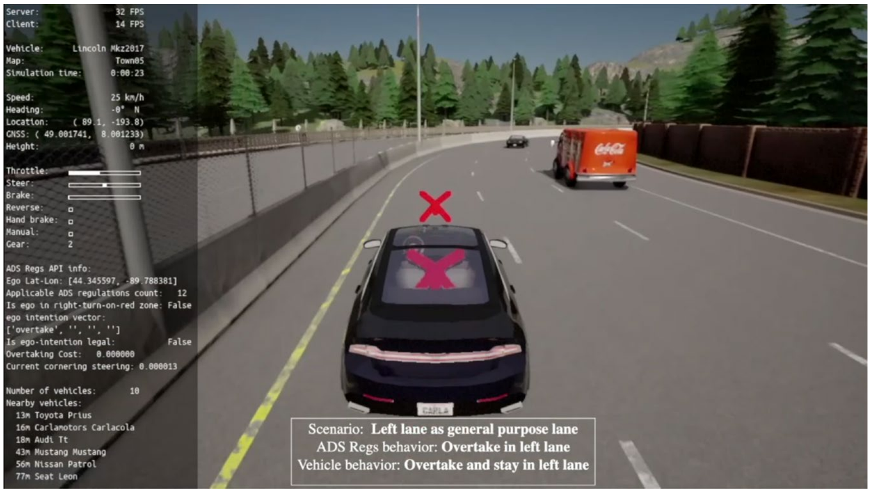
The second scenario concerns traffic regulations at freeway segments, i.e., whether the left lane on a multi-lane freeway roadway can be used as a general-purpose traveling lane or overtaking lane only. The specific details of the scenario are as follows:

- Multi-lane freeway environment (minimum two lanes).
- Left lane is dedicated as passing lane or as general traveling lane.
- This may result in different lane change and over-taking behaviors.
- Traffic stream contains both automated vehicles and human-driven vehicles.

The simulation demonstration and results are shown in figure 22. In figure 22(a), an ADS-equipped vehicle initiated a lane change to the left because of a slow-moving vehicle in the front. This overtaking behavior is originally embedded in the simulated ADS platform as a baseline function for driving efficiency. In figure 22(b), the vehicle has completed the lane-change maneuver and continues to plan trajectories that keep itself in the left lane. This is because the data from the traffic regulations database indicate that the left lane can be used as the general traveling lane, and there is also no motivation (e.g., efficiency saving to overtake slow-moving front vehicle) for this vehicle to change lanes back to the middle lane. This is also the default logic in the simulated ADS platform. However, in figure 22(c), the left lane can only be used as the overtaking lane, and therefore, the vehicle replans its behavior and trajectory to change the lane back to the middle lane, even though there are no slow-moving vehicles in front of the vehicle in the left lane. This is because the PLAN Stack imposes a heavy penalty on the trajectories that keep the vehicle in the left-most lane, and therefore the ADS will then select a trajectory back to the middle lane that is rated higher by the PLAN Stack.



(a) Vehicle initiating lane change for overtaking.



(b) Vehicle operating in the left lane after overtaking.

(c) Vehicle returning to the right lane after overtaking.

Source: FHWA.

Figure 22. Illustration. Freeway overtaking demonstration.

The demonstration successfully connects the traffic regulations database prototype with the simulated example ADS platform. More importantly, the simulation shows the necessity of providing such data to ADS-equipped vehicles for them to operate safely and legally on national highways. The demonstration of both scenarios also shows the generation of unique operational behaviors when the same ADS software operates on the same highway facilities both with and without the regulation being accounted for. The demonstration indicates the need for both IOOs and ADS developers to explicitly consider the impacts of traffic regulations on ADS operational behavior. As proven in this study, IOOs and ADSs need to provide streamlined interfaces in the development of ADS platforms, traffic regulation database, and the entire ADS ecosystem.

SIMULATION REPOSITORY

The simulation source codes, along with the traffic regulations database, are open to the public through the GitHub repository[7] for the simulation scripts, videos, and documentation. The codes are designed to demonstrate the implementation of integration between traffic laws and regulations database framework and ADS-equipped vehicle platform. The codes for both the intersection and freeway scenarios are uploaded. The ADS-equipped vehicles are modeled at different locations using the same database. The instructions for setting up the simulation environment are also provided on the GitHub repository.

[7] GitHub. 2021. "ads-traffic-regs." (website). https://github.com/usdot-fhwa-stol/ads-traffic-regs/tree/cherneysp-initial, last accessed December 7, 2021.

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February 2023
FHWA-HOP-21-040