Automated Driving Systems Operational Behavior and Traffic Regulations Information: Model Plan

FHWA-HOP-21-039 July 2024

U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td colspan="2">1. Report No.
FHWA-HOP-21-039</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="4" rowspan="2">4. Title and Subtitle
Automated Driving Systems Operational Behavior and Traffic Regulations Information: Model Plan</td><td colspan="2">5. Report Date
April 2024</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="4">7. Authors
Kyle Garrett, Jiaqi Ma, Bryan Krueger, Abby Morgan, Ron Schaefer</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="4" rowspan="2">9. Performing Organization Name and Address
Leidos, Inc.
11251 Roger Bacon Drive
Reston, VA 20190
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Synesis Partners, LLC
Kittelson & Associates, Inc.</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
693JJ319F000345</td></tr>
<tr><td colspan="4" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Draft Technical Report
July 2020–January 2021</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HOP</td></tr>
<tr><td colspan="6">15. Supplementary Notes
Government Task Manager: Kingsley Azubike</td></tr>
<tr><td colspan="6">16. Abstract
This model plan investigates the challenges of establishing an automated driving system (ADS)-ready database of traffic laws and regulations, as well as access and exchange interfaces to support sharing information within the ADS ecosystem. It also identifies and facilitates basic interfaces for State and local traffic code stakeholders and ADS behavior subject matter experts to collaborate. This model plan synthesizes results and conclusions from research into the relationship between traffic regulations and ADS behaviors to create a roadmap for scaling the prototype framework to a more complete model that can accommodate complex applications in a heterogeneous ADS ecosystem. The plan is designed for collaboration involving infrastructure owner-operators, traffic regulation and code practitioners, ADS practitioners, software developers, and Government agencies. The plan is comprehensive enough to serve as helpful information for future deployment of an integrated ADS-ready traffic laws and regulations digital framework.</td></tr>
<tr><td colspan="3">17. Key Words
Automated driving systems (ADS); traffic laws and regulations; Uniform Vehicle Code (UVC); database</td><td colspan="3">18. Distribution Statement
No restrictions.</td></tr>
<tr><td colspan="2">19. Security Classif. (this report)
Unclassified</td><td colspan="2">20. Security Classif. (this page)
Unclassified</td><td>21. No. of Pages
66</td><td>22. Price
N/A</td></tr>
</table>

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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ADS	automated driving system
API	application programming interface
AV	automated vehicle
AVSC	Automated Vehicle Safety Consortium
CAMP	Collision Avoidance Metrics Partnership
CDA	cooperative driving automation
COU	concept of use
CSV	comma-separated values
DAVI	Data for Automated Vehicle Integration
DDT	dynamic driving task
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
GNSS	global navigation satellite systems
HIL	hardware-in-the-loop
IOO	infrastructure owner-operator
ITS	intelligent transportation system
JSON	JavaScript Object Notation
LiDAR	light detection and ranging
MUTCD	*Manual on Uniform Traffic Control Devices*
NCSL	National Council of State Legislatures
NHS	national highway system
NHTSA	National Highway Transportation Safety Administration
NTCIP	National Transportation Communications for Intelligent Transportation Systems (ITS) Protocol
ODD	operational design domain
PDF	portable document format
POC	proof of concept
radar	radio detection and ranging
SCMS	Security Certificate Management System
SIL	software-in-the-loop
SME	subject matter expert
TM	traffic management
USDOT	U.S. Department of Transportation
URI	uniform resource identifier
URL	uniform resource locator
UVC	*Uniform Vehicle Code*
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
WZAD	work zone activity data
WZDI	Work Zone Data Initiative
WZDx	Work Zone Data Exchange
XIL	everything-in-the-loop

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 systems management and operations strategies. Infrastructure owner-operators (IOOs) and their partner agencies across the United States have been grappling with 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. This underscores the need for practice-ready information and tools that IOOs can use for planning and deploying resources and policies for integrating ADS. Key insights from the National Dialogue on Highway Automation[1] include a need for a national vision; increased public awareness and support; agency education; enhanced planning to include probabilistic and scenario-based planning; and data exchange, standardization, and management.

National automation readiness involves a strategic understanding of the context of automated vehicles (AVs) and the national transportation infrastructure. The Federal Highway Administration (FHWA) has been exploring this context through assessing information and data needs for AV, the National Dialogue on Highway Automation, and other FHWA leadership and working groups. The 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 input for Federal, State, and local AV implementation initiatives. IOOs want 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.

Public and private stakeholder access to data is a key enabler of safe, efficient, and accessible integration of AVs into the transportation system. On Thursday, 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 the "One DOT" approach to Federal AV policy as originally described in the USDOT *Automated Vehicles 3.0*[3] guidance document, and marked a new phase of dialogue with public and private sector stakeholders to accelerate the safe deployment of AVs.

The Roundtable identified the following high-priority use cases for data exchange:

- Monitoring planned and unplanned work zones

[1]FHWA. n.d. "National Dialogue on Highway Automation" (web page). 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*. Washington, DC: USDOT. https://www.transportation.gov/av/data/roundtable-data-automated-vehicle-safety-summary-report, last accessed May 11, 2020.

[3]USDOT. 2018. *Preparing for the Future of Transportation: Automated Vehicles 3.0*. Washington, DC: USDOT.

- Providing real-time road conditions
- 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 can facilitate the development of ADS behavior and roadway adaptations that fulfill the vision of safe and effective ADS operations. Building an ADS operational behavior and traffic regulation database framework could be a key aspect of realizing effective, robust digital transportation systems for AV integration. It will consist of a comprehensive, structured database of traffic regulations that developers could use to set basic programming standards regarding traffic regulations.

ADS developers face challenges in accounting for the multitude of static and dynamic traffic regulations, providing the regulatory information to ADS, and determining how the system would be implemented across the Nation. Traffic regulation information varies in format, structure, and implementation among jurisdictions that enact and enforce those regulations across the country. Without common data exchanges, it is almost impossible to develop ADS software that can ensure optimal ADS performance under varying sets of traffic regulations. ADS development would benefit from 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 the access and exchange requirements to support the sharing and consumption of the information within the ADS ecosystem. It also identifies the basic needs for collaboration among State and local traffic code stakeholders and ADS behavior subject matter experts (SME) in automation technology development, vehicle manufacturing, and operations.

For consistency, interoperability, and support of other databases of existing traffic regulations and their interaction with ADS, it is important to develop a comprehensive database framework to support the incorporation of all traffic regulations that enable ADS behavior development and operation. The goal is to facilitate a traffic regulation specification that supports development and subsequent operations of traffic with ADS-equipped vehicles. This project involves:

- Analysis of ADS readiness of the current traffic laws and regulations databases
- Development of a concept of use (COU)
- Design of a prototype of the traffic laws and regulations database framework
- Demonstration of a proof-of-concept (POC) laboratory testbed simulation
- Development of a model plan for a future implementation of AV integration with the traffic laws and regulations database framework

This model plan synthesizes results and conclusions from research into the relationship between traffic regulations and ADS behaviors into a roadmap for scaling the prototype framework to a more complete model that can accommodate complex applications in a heterogeneous ADS ecosystem. The plan is designed for collaboration involving IOOs, traffic regulations and code practitioners, software developers, government agencies, and ADS practitioners in technology companies, vehicle manufacturers, fleet and freight logistics companies, universities, and research laboratories. The plan can serve as helpful information for future deployment of an integrated ADS-ready traffic laws and regulations digital framework.

The following section describes each of the chapters:

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

Chapter 2. Model Plan. This chapter describes the model plan.

Chapter 3. Operational Concept. This chapter describes the operational concept for the ADS regulations data framework.

Chapter 4. Framework Requirements. This chapter describes the functional, interface, security, performance, and standards requirements for the framework.

Chapter 5. Design and Implementation. This chapter describes the design and implementation of the traffic regulations data framework.

Chapter 6. Verification and Validation Plan. This chapter describes the verification and validation testing plan.

CHAPTER 2. MODEL PLAN

This chapter describes the goals, scope, activities, and schedule for further development of an ADS traffic regulations data framework. This model plan will use and build on lessons learned in the current research.

GOALS AND OBJECTIVES

The goal of the model plan is to describe the activities, stakeholders, and timelines to develop a traffic regulations model that can accommodate complex applications in a heterogeneous ADS ecosystem. The plan intends to:

- Demarcate and validate the model context relative to the AV and ADS ecosystem and its stakeholders.
- Describe the operational concept and requirements more fully, especially as they relate to the range of use cases accommodated by the model for ADS development and operations; the roles of stakeholders; and agreements that may be necessary to establish, operate, and maintain the model.
- Amend and validate the model architecture in consideration of the revised operational concept, interfaces, and applicable standards.
- Describe the activities to be undertaken in developing and populating the model.
- Propose methods for verifying and validating the model.
- Propose means of operating and maintaining the model.

The purpose of the model is to enable an entity or agency, working with the ADS ecosystem stakeholders, to develop and deploy a workable comprehensive framework and interfaces for providing traffic regulations data to developers and their systems. The model will be based on the prototype framework and lessons learned in previous tasks in this project.

MODEL SCOPE

This model plan is intended to develop a means of providing traffic regulations data for U.S. jurisdictions to ADS and ADS developers. The model plan does not address the specific applications of the traffic regulations data to operational design domains (ODD). ADS developers assign the ODD definitions for their particular systems and map them to the relevant traffic regulations. The model plan does not provide explicit interpretation or extension of traffic regulations as they might apply to ADS. The model plan does not suggest or specify a means of normalizing or standardizing traffic regulations across or among U.S. jurisdictions. The model plan does not make representations about its application or utility outside the United States.

DEFINITIONS

The following technical terms are used within this document:

- ADS: "The hardware and software that are collectively capable of performing the entire *dynamic driving task (DDT)* on a *sustained* basis, regardless of whether it is limited to a specific *operational design domain (ODD)*; this term is used specifically to describe a level 3, 4, or 5 *driving automation system*."[4]

- AV: A vehicle under the control of an ADS rather than a human driver.[5]

- Driving automation system: "The hardware and software that are collectively capable of performing part or all of the *DDT* on a *sustained* basis; this term is used generically to describe any system capable of level 1–5 *driving automation*."[6]

- DDT: "All of the real-time operational and tactical functions required to *operate* a *vehicle* in on-road traffic, excluding the strategic functions such as *trip* scheduling and selection of destinations and waypoints, and including without limitation:

    - Lateral vehicle motion control via steering (operational)
    - *Longitudinal vehicle motion control* via acceleration and deceleration (operational)
    - *Monitoring* the driving environment via object and event detection, recognition, classification, and response preparation (operational and tactical)
    - Object and event response execution (operational and tactical)
    - Maneuver planning (tactical)
    - Enhancing conspicuity via lighting, signaling and gesturing, etc. (tactical)"[7]

- ODD: "Operating conditions under which a given *driving automation system* or *feature* thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."[8]

- Traffic regulation: a rule or directive for the operation of a vehicle on roadways within the jurisdiction of the legal authority promulgating the regulation.

- Traffic code: a compilation of traffic rules (e.g., the *Uniform Vehicle Code*[9] (*UVC*)).

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[4]SAE International. 2018. *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. SAE J3016, Section 3. Warrendale, PA: SAE International.

[5] SAE International does not include this definition in SAE J3016™; it focuses on driving automation systems rather than on the vehicle.

[6]Ibid.

[7]Ibid.

[8]Ibid.

[9]National Committee on Uniform Traffic Laws and Ordinances (NCUTLO). 2000. *Uniform Vehicle Code.* Alexandria, VA: NCUTLO.

STAKEHOLDERS

Populating and maintaining the traffic regulations model framework for ADS will need input from multiple groups of stakeholders distinct from the framework's ultimate users. The framework is sustainable if it is fully populated and regularly updated as regulations change. The framework is valuable if users provide constructive feedback to address any errors or challenges with the framework content, access, or structure and if managers address this feedback in a timely manner.

Stakeholders who provide input to the model framework are:

- Traffic code service authorities and providers
- Traffic code enforcement agencies
- Legislatures
- Regional and local planning agencies

Stakeholders who maintain the framework or who clarify the rules are:

- Traffic code practitioners
- IOOs
- Traffic code service authorities and providers
- Traffic code enforcement agencies

Stakeholders who use and provide feedback to strengthen the framework are:

- ADS developers
- Vehicle and fleet operators
- Insurers
- Traffic control practitioners

These stakeholders can come together to develop and maintain the model framework through a volunteer task force, working group, or formal partnership agreements. A task force or working group can bring these diverse stakeholders together to understand how the model framework could be used and to get support for the development and maintenance of the framework without mandating participation. This task force could set goals for maintaining and updating the information in the data framework and could hold themselves accountable to its quality and maintenance.

The transportation community has used volunteer task forces and working groups to successfully manage other model frameworks. The Transportation Research Board Committee on Highway Capacity and Quality of Service maintains the *Highway Capacity Manual*.[10] The American Association of State Highway and Transportation Officials (AASHTO) Technical Committee on Geometric Design maintains its *Policy on Geometric Design of Highways and Streets*[11] (also

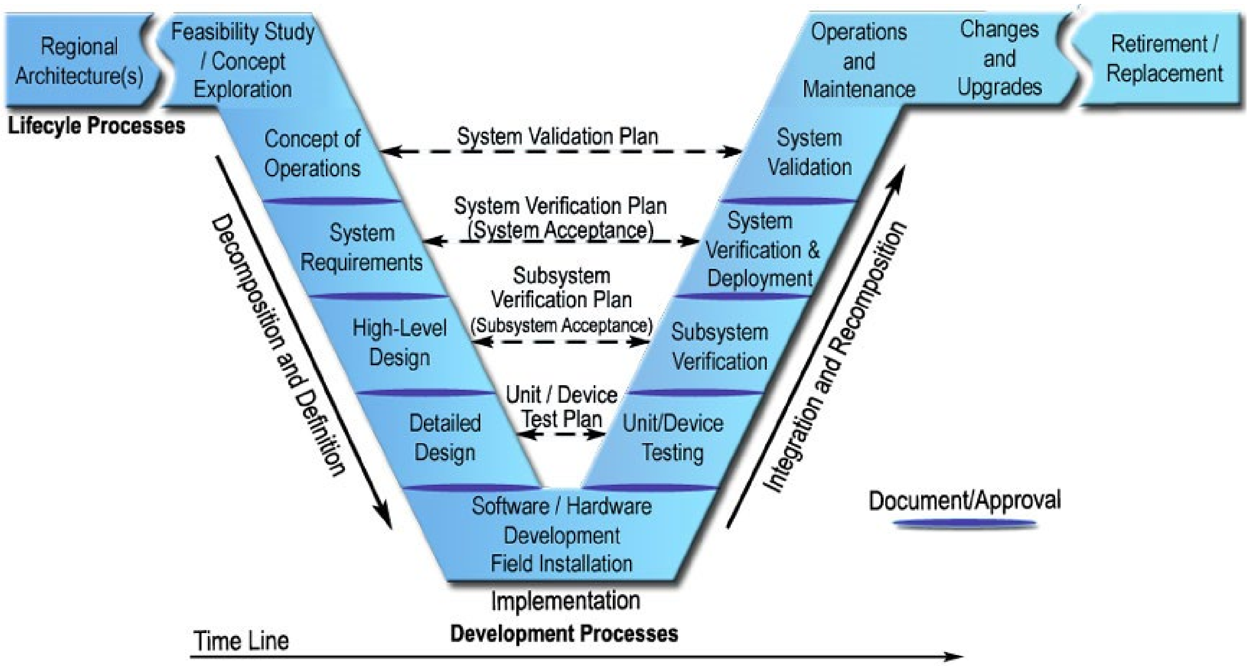
[10]Elefteriadou, L. A. 2016. *Highway Capacity Manual, 6th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24798, last accessed December 16, 2022.

[11]AASHTO. 2018. A Policy on Geometric Design of Highways and Streets. 7th ed. Washington, DC: AASHTO.

called the AASHTO Green Book). Another way to ensure ongoing participation by key stakeholders is through partnership agreements. The Collision Avoidance Metrics Partnership (CAMP) brought together original equipment manufacturers to collaborate with USDOT on precompetitive crash avoidance research.

DEPLOYMENT ACTIVITIES

This model plan describes activities needed to deploy an ADS traffic regulations data framework, in terms of a systems engineering process consistent with intelligent transportation systems (ITS) development practices, typified by the "V" diagram in figure 1. The activities described in this section align with the activities and deliverables in the systems engineering model.



Source: Federal Highway Administration.

Figure 1. Diagram. Systems engineering "V" model.

Convene Stakeholders

The initial activities will convene stakeholders to explore the concept, confirm this model plan, and start their engagement throughout the development process. They will be asked at the start of the project to review work that has been completed to date, provide perspectives on development needs, and anticipate their involvement in deployment. Stakeholders will receive updates on development progress and will be asked to review work products from the downstream development activities. Stakeholders may be asked to participate in demonstrations of the developed framework and its operations. A stakeholder engagement plan will document their intended involvement.

Revise the Operations Concept

Research to date has provided insight on the relationship between traffic regulations and ADS development and has demonstrated a concept for providing traffic regulations data to ADS and its developers. This set of model plan activities will revise the operations concept based on the lessons learned, gaps identified, and next steps described later in this model plan and discussion of the prototype. Revisions to the operations concept may include:

- Adjusting the scope and context of the framework as appropriate to remain current with industry directions and events
- Expanding the user needs based on stakeholder reviews
- Reviewing and updating the prototype architecture as appropriate based on scope and user needs
- Identifying and describing use cases to accommodate the breadth of identified user needs and situations described in existing bodies of traffic regulations
- Describing potential governance, operations, and maintenance models for the framework

The revised operations concept should particularly address the relationships between the system use cases and ODDs as potential system users may define them.

Formalize Requirements

Work that has been completed on the prototype traffic regulations data framework has proceeded from a broad initial perception of user needs. It has not included a formal mapping of user needs to requirements. Further development will benefit from a more structured analysis of system requirements for the data framework. This analysis should include:

- Functional requirements
- Interface requirements
- Security requirements
- Performance requirements
- Applicable standards

Update the System Design

Although a prototype framework was developed and successfully demonstrated in the previous task, the system design did not address all factors that might arise in consideration of formalized requirements. The system architecture will need to be expanded and revised from the prototype design, identifying components and relationships needed to address each requirement. The design refinement will also specify the system interfaces, recognizing the potential to work with existing and developing industry standards.

Develop Scalable Model System

The regulations data framework will be (re)developed to fulfill the updated design. Development may use components from the prototype system but should meet the fully specified requirements developed under this model plan.

Populate the System

Testing and demonstrating the regulations data framework will involve populating the framework with regulations data. The data will be collected from and referenced to available public traffic regulations data sources. The resulting data collection should demonstrate a complete data space in each of two dimensions. It should demonstrate a complete synthesis of traffic regulations for at least one U.S. State or jurisdiction, and it should demonstrate a complete synthesis of traffic regulations for at least one traffic situation (e.g., stopping at a red traffic signal) across all U.S. State and territorial traffic codes.

Verify to Requirements

The completed, populated data framework will be tested to demonstrate that it meets the requirements specification. At a minimum, the system functions will be tested by exercising the programming interfaces with custom test applications. Alternatively, testing can use a software simulation to exercise all features in a variety of use cases. Humans, who can address intended behaviors and potential error states associated with inappropriate inputs and behaviors, are most effective at testing requirements on user interfaces.

Validate to Stakeholder Needs

Following the "V" diagram, the validation process works backward from the as-built system to user needs to ensure the system fulfills operational intent and functional specification. At a minimum, the stakeholder community will review and exercise the system. To address an aggregated view of user needs, an ADS simulation may exercise the automated functions the regulations data framework provides. This model plan is designed to be used in developmental practice by one or more stakeholder ADS developers and their systems and through collaboration with a publicly supported ADS development effort or a State-sponsored project.

Operate and Maintain the Model System

The model system will be operated and maintained for stakeholder use and evaluation over a specified period of time. The specifics of its operations and maintenance will depend on the deployment model and governance as identified in the operations concept. These governance models could include:

- Distributed service provided by the State and local governments promulgating the regulations
- Service operated by USDOT or a USDOT contractor

- Service provided by a nongovernmental institution or association on behalf of member agencies
- Service provided by private operators working to standard interfaces and certifications

CHAPTER 3. OPERATIONAL CONCEPT

This chapter describes the operational concept for the traffic regulations data framework for ADS based on the COU prepared in a prior task for this project.[12]

DESCRIPTION OF THE DATA ENVIRONMENT

The traffic regulations data environment specifies the rules of the road that an ADS must follow. These rules may vary by jurisdiction, roadway type, operating environment, or other constraints. For example, in New York City, vehicles are prohibited from turning right at a red traffic signal; however, this movement is allowed in other municipalities throughout the State. Some States require drivers to use headlights when windshield wipers are active during a rain event. Additionally, time-of-day requirements for headlight use vary among States. ADS developers could benefit from a data framework that combines these traffic rules and regulations into a format that is searchable based on jurisdiction, road network, operational environment, and other criteria. This chapter explains how the rules of the road are established, how they vary between jurisdictions, and how they apply to ADS operations.

Roadway Network and Infrastructure

The U.S. roadway system is a complex network that connects roads of different sizes to provide people and goods access across communities and borders. One way U.S. roads are classified is by functional classification. The functional classification of roadways defines the role each roadway network element plays in serving travel needs.[13] Transportation agencies describe roadway system performance, benchmarks, and targets by functional classification. Federal legislation uses functional classification to determine funding under the Federal-aid program.

Some traffic regulations are also categorized by functional classification. For example, pedestrians and bicyclists are prohibited from using interstate highways. Additionally, many States have adopted minimum speed requirements for interstates, but they do not post or enforce minimum speed requirements on local roads. Roadway infrastructure also sets the application of some traffic rules and regulations. For example, all States have a rule that requires vehicles to come to a stop at red traffic signals. Developing a model traffic regulations data framework starts with understanding traffic laws and regulations in the United States, and ADS developers need to understand the rules of the road and how they vary across roadway functional classification or in the presence of different roadway infrastructure.

Overview of Traffic Laws and Regulations

The States, rather than the Federal Government, enact and administer traffic regulations in the United States. Connecticut enacted the first statewide traffic regulations in 1901,[14] before

[12]Garrett, K., J. Ma, and A. Morgan. 2020. Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information: Concept of Use. Report No. FHWA-HOP-20-041. Washington, DC: FHWA.

[13]FHWA. 2013. Highway Functional Classification Concepts, Criteria, and Procedures, 2013 ed. Washington, DC: FHWA.

[14]State of Connecticut. "An Act Regulating the Speed of Motor Vehicles," in Public Acts Passed by the General Assembly of the State of Connecticut, in the Year 1901, Chapter 69.

automobiles were common on roadways. Other States enacted their own regulations as need and custom dictated. The first version of the *UVC* appeared in 1926.[15] AASHTO compiled the first *Manual on Uniform Traffic Control Devices*[16] (*MUTCD*) in 1935.[17]

In 1966, USDOT was established. Although not directly responsible for traffic regulation, USDOT oversees the safety of the Nation's roadways. As described in the Moving Ahead for Progress in the 21st Century Act,[18] the Secretary of Transportation, under Chapter 4 of Title 23 of the United States Code (U.S.C.), "[i]s authorized and directed to assist and cooperate with other Federal departments and agencies, State and local governments, private industry, and other interested parties, to increase highway safety."[19] This authority is exercised through the Department's review and approval of the States' highway safety programs. The National Highway Transportation Safety Administration (NHTSA) and FHWA Office of Safety administer highway safety programs within USDOT.

Most aspects of the national body of traffic regulations are consistent as a result of historical practices, institutional collaborations, and modern Federal oversight. The *UVC*[20] represents a working consensus. It has no formal standing as a body of law and has not been updated since 2000. As a starting point for this analysis, the *UVC* provides a common reference for the definitions of terms used in framing traffic regulations and the user categories to which the regulations apply. The structure of the *UVC* has also been echoed in many of the States' traffic codes, forming a *de facto* standard for indexing the regulations. Similarly, the *UVC* and State traffic codes generally point to the *MUTCD*, or the State's version, for definitions of particular traffic control devices with which to comply.

The advent of AVs creates multiple challenges for traffic regulations. Much of the body of traffic safety regulation concerns licensure of vehicles and drivers, and not specifically their behaviors. AVs blur the distinction between driver and vehicle, since driving automation systems reside in the vehicle and depend on the vehicle's sensors. Recent State-level AV regulations broadly view AVs as a hybrid of vehicles and drivers. Regulation is largely limited to the licensure of AVs for ODDs in particular jurisdictions, under the presumption that existing regulations on driver behavior will apply.

Existing Traffic Laws and Traffic Regulation Databases

The body of traffic laws in the United States varies from State to State and among local jurisdictions within States. Reviewing existing traffic laws and traffic regulation databases involves considering regulations across the United States as a whole and considering State and local perspectives.

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[15]Davis, J. A. 1963. *The California Vehicle Code and the Uniform Vehicle Code*. 14 Hastings L.J. 377. https://repository.uchastings.edu/hastings_law_journal/vol14/iss4/3, last accessed December 16, 2022.

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

[17]FHWA. n.d. "The Evolution of *MUTCD*." https://mutcd.fhwa.dot.gov/kno-history.htm, last accessed May 11, 2020.

[18]GovInfo. 2012. *Moving Ahead for Progress in the 21st Century Act*, Pub. L. No. 112-141.

[19]GovInfo. 2012. *23 U.S.C. § 401. Authority of the Secretary*, Washington, DC.

[20]NCUTLO. 2000. *Uniform Vehicle Code.* Alexandria, VA: NCUTLO.

U.S. Perspective

Because there are no national statutes requiring conformance to a single standard, and consequently no normative statutes, there have been various other efforts to document the actual diversity of traffic laws across the United States. Particular perspectives and use cases for the resulting traffic regulation compilation or database have driven each effort. For example:

- Commercial services publish many of the bodies of State statutes, including traffic regulations, online.
- The Digest of Motor Laws[21] provides summaries of traffic laws in individual States and across the United States.
- The National Council of State Legislatures (NCSL) maintains a database of current legislation relating to traffic safety.
- NCSL also provides a database of legislation directly related to AVs.
- The National District Attorneys Association maintains a National Traffic Laws Center to support district attorneys in enforcing traffic law. It does not specifically provide a database of laws.
- The FindLaw website[22] provides summaries and links for some State traffic laws. It appears to be intended for individual research on traffic law enforcement and penalties for traffic law violations.
- The American Road and Transportation Builders Association maintains a National Work Zone Safety Information Clearinghouse[23] of links to work zone safety laws across States and territories.

State Perspectives

Vehicle and traffic laws in each State are within the authority of the State legislatures. Execution and enforcement of those laws reside with the State motor vehicle administration, transportation, and police/patrol agencies, which may be separate or combined in various ways. Publishing enacted vehicle and traffic statutes is a legislative function. State transportation agencies are as much users of those statutes as drivers within those States.

Although traffic laws across the United States are largely consistent and, in many cases, based on the *UVC*, available publications and databases of State traffic laws vary in structure, format, and wording. Electronic access to State traffic laws ranges from portable document format (PDF) of

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[21]AAA. 2022. “Digest of Motor Laws” (web page). https://drivinglaws.aaa.com/, last accessed May 12, 2020.
[22]Thomson Reuters. 2022. “State Laws” (web page). https://statelaws.findlaw.com/, last accessed December 16, 2022.
[23]American Road & Transportation Builders Association. 2022. “Laws, Standards & Policies” (web page). https://www.workzonesafety.org/data-resources/laws-regulations-and-standards/state-work-zone-laws/, last accessed October 25, 2019.

entire sections of the statutes to searchable records of individual statutes. A detailed compilation of references to State statutes is provided in table 2 of the *Detailed Analysis of ADS-Deployment Readiness of the Existing Traffic Laws and Regulations*.[24]

The *MUTCD* provides another layer of consistency in traffic control devices that complements the influence of the *UVC*. The MUTCD provides the national standards for traffic control devices but includes significant flexibility to account for individual jurisdiction preferences. State traffic codes prescribe the State's standard for traffic control devices that codifies individual state preferences. FHWA maintains an informational web page[25] linking to the States' traffic control device specifications. Some States may provide detail beyond the State traffic code with databases of information on deployed traffic control. For example, Ohio provides records of permits to local agencies for traffic controls such as speed zones, traffic signals, and signs on State routes.[26] However, no national databases of traffic control device deployments exist.

Local Perspectives

Vehicle and traffic laws may be subject to additional local regulation where allowed (or not disallowed) by State authority. These local authorities may include counties, parishes, cities, villages, or townships. The vast number and diversity of local authorities and their transportation agencies preclude cataloging their traffic regulations databases for this analysis, other than anecdotally. In general, the local regulations reference the State laws with which the local law conforms.

ADS and Operational Behaviors

ADS-equipped vehicles are cyberphysical systems that can be abstracted into sensing, computing, and actuation modules. Sensing devices, such as laser scanners (light detection and ranging) and cameras, are typically used for driving automation in urban areas. Actuation modules handle steering and throttle, and the trajectory planning and tracking module typically generates the control commands. Computation is a major component of self-driving technology. Scene recognition, for instance, is handled by the localization, detection, and prediction modules, whereas path planning is handled by mission- and motion-based modules. Each module employs its own set of algorithms.

Figure 2 shows the basic control and data flow for an automated vehicle. Sensors record environmental information that serves as input data for the artificial intelligence core. The artificial intelligence core includes data fusion for vehicle localization based on filtering techniques, machine learning methods for predicting other vehicles' behavior, and intelligent decisionmaking in mission/motion planning using optimal control or reinforcement learning

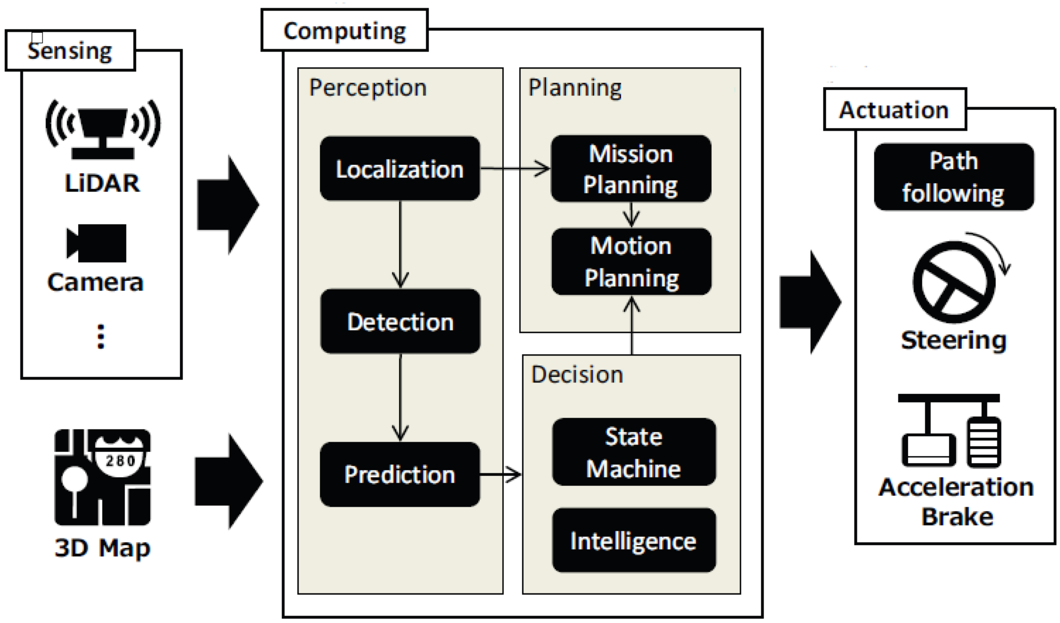
[24]Ma, J., K. Garrett, and A. Morgan. 2020. *Detailed Analysis of ADS-Deployment Readiness of the Existing Traffic Laws and Regulations*. Report No. FHWA-HOP-20-013. Washington, DC: FHWA.

[25]FHWA. n.d. "MUTCDs & Traffic Control Devices Information by State" (web page). https://mutcd.fhwa.dot.gov/resources/state_info/index.htm, last accessed May 12, 2020.

[26]Ohio Department of Transportation. n.d. "Traffic Regulations" (web page). https://www.transportation.ohio.gov/wps/portal/gov/odot/programs/traffic-regulations/traffic-regulations, last accessed December 31, 2019.

approaches. Three-dimensional maps are becoming commonplace for self-driving systems, particularly in urban areas, to complement the planning data available from sensors. External data sources can improve the accuracy of localization and detection without increasing the complexity of the vehicle's algorithms. Artificial intelligence cores typically output values for angular and linear velocities, which serve as commands for steering and braking, respectively.

In SAE J3016™ Levels of Driving Automation, shown in figure 3, a driving mode is a type of driving scenario with specific DDT requirements (e.g., expressway merging, high-speed cruising, low-speed traffic jam, and closed-campus operations). A particular shift occurs from SAE Level 2 to SAE Level 3: The human driver no longer has to actively drive when the corresponding automated driving features are activated. This is the final aspect of the DDT that is now passed over from the human to the automated system. At SAE Level 3, the human driver still has the responsibility to intervene when asked to do so by the automated system. At SAE Level 4, the human driver is relieved of that responsibility, and at SAE Level 5, the automated system will never need to ask for an intervention.



3D = three-dimensional. LiDAR = light detection and ranging.

Source: Autoware.

Figure 2. Diagram. Automated driving vehicle platform.

		RELATIONSHIP BETWEEN CLASSES OF COOPERATIVE DRIVING AUTOMATION J3216™ AND LEVELS OF AUTOMATION J3016™					
			Partial Automation of Dynamic Traffic Task		Complete Automation of Dynamic Traffic Task		
		SAE® Level 0	**SAE® Level 1**	**SAE® Level 2**	**SAE® Level 3**	**SAE® Level 4**	**SAE® Level 5**
		No driving automation (human does all driving)	Driver assistance (longitudinal OR lateral vehicle motion control)	Partial driving automation (longitudinal AND lateral vehicle motion control)	Conditional driving automation	High driving automation	Full driving automation
NO COOPERATIVE AUTOMATION		E.g., Signage, Traffic control devices	Relies on driver to complete the dynamic traffic task and to supervise feature performance in real time		Relies on automated driving systems to perform complete dynamic traffic tasks under defined conditions (fallback condition performance varies between levels)		
CDA CLASSES							
SAE® CLASS A STATUS SHARING	Here I am and what I see	E.g., Brake lights, traffic signal	Potential for improved object and event detection(a)		Potential for improved object and event detection(b)		
SAE® CLASS B INTENT SHARING	This is what I plan to do	E.g., Turn signal, merge	Potential for improved object and event detection(a)		Potential for improved object and event detection(b)		
SAE® CLASS C AGREEMENT SEEKING	Let's do this together	E.g., Hand signals, merge	Not Applicable		Cooperative automated driving systems designed to attain mutual goals through coordinated actions		
SAE® CLASS D PRESCRIPTIVE	I will do as directed	E.g., Hand signals, lane assignment by officials	Not Applicable		Cooperative automated driving systems designed to accept and adhere to a command		

(a) Improved object and event detection and prediction through CDA Class A and Class B status and intent sharing may not always be realized given that Level 1 and 2 driving automation features may be overridden by the driver at any time, and otherwise have limited sensing capabilities compared to Level 3, 4, and 5 ADS-operated vehicles. (b) Class A and B communications are one of the many inputs to an ADS's object and event detection and prediction capability, which may not be improved by the CDA message.

Figure 3. Illustration. Definitions of levels of driving automation.

Based on the understanding of ADS software structure, any ADS component under different rules and regulations can affect ADS operational behavior. For example, yellow traffic signal indications and timing may vary along and among urban corridors, such that when an AV detects a yellow indication, how it interprets the rule may be dramatically different, which will then change the time when the vehicle can pass the stop bar at the intersection and, in turn, have an effect on the trajectory planning process of the AVs. Another example involves the use of the leftmost lane on freeways (e.g., overtaking only or regular driving). If the lane can only be used as an overtaking lane, the ADS planning module will always ask the vehicle to change back to the original lane after it passes the front slow-moving vehicle. Compared with the other condition (i.e., used as a regular driving lane), this traffic rule can result in frequent lane-change behavior on freeways, causing inefficient traffic operations. This demonstrates how different traffic laws and regulations can result in dramatically different ADS behaviors, even with the same ADS software. To ensure safe and efficient ADS behavior, it is key to provide ADS

[27]"SAE International. 2018. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE J3016. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j3016_201806/, last accessed December 16, 2022.

vehicles with accurate traffic regulation information and to design ADS software to explicitly incorporate the regulations.

ADS only involves single-vehicle automation through onboard sensing and computing. SAE International is working on a new standard, SAE J3216_202005™,[28] to define cooperative driving automation (CDA), which enables and supports ADS automation through machine-to-machine communications. CDA becomes even more relevant when traffic regulation databases are shared with AVs enabled with CDA to communicate this information.

Emerging AV Data Frameworks

USDOT has facilitated agreements among industry and non-Federal governments on common data formats that lower the cost of data exchange. This section focuses on the two most recent frameworks related to ADS.

Data for Automated Vehicle Integration (DAVI)

USDOT launched DAVI[29] to identify, prioritize, monitor, and address data exchange needs for AV integration across the modes of transportation. Lack of access to data could impede AV integration and delay safe introduction. The DAVI framework provides a common language for identifying and prioritizing data exchange needs across traditional silos. It helps stakeholders working on diverse aspects of AV integration understand each other's data needs and learn from successful exchanges as they emerge. The framework defines key categories, goals, participants, and priorities of data exchanges identified by the department's stakeholders, such as work zone data needed for AVs to navigate safely.

USDOT's Roundtable on Data for Automated Vehicle Safety discussed potential priorities for voluntary data exchanges to accelerate safe AV integration. The Department kicked off the Work Zone Data Exchange[30] (WZDx) in March 2018 to take on a priority identified at the roundtable. The summary notes also called for enhanced inventories for roadways, which include high-definition maps already being developed. Creating inventories of fixed objects on the road, such as traffic signs, is not a difficult task, and private sectors have done it for many locations. The rules behind the infrastructure (i.e., traffic laws and regulations) could also be part of the map. Unfortunately, no complete digital database exists that addresses this issue.

WZDx and Work Zone Data Initiative (WZDI)

The purpose of WZDI is to develop a model practice for managing work zone activity data (WZAD) and to create a consistent language, through a data dictionary and supporting implementation documents, for communicating work zone activity information across jurisdictional and organizational boundaries. The effort promotes a stakeholder- and

[28]SAE International. 2020. *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. SAE J3216_202005. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j3216_202005/, last accessed December 16, 2022.

[29]USDOT. n.d. "Data for Automated Vehicle Integration (DAVI)" (web page). https://www.transportation.gov/av/data, last accessed December 16, 2022.

[30]USDOT. n.d. "Work Zone Data Exchange (WZDx)" (web page). https://www.transportation.gov/av/data/wzdx, last accessed December 16, 2022.

systems-driven perspective for WZAD that serves the emerging need for improved real-time road condition information, as well as traditional operations management, which benefits from improved data portability throughout project life cycles. This initiative seeks a shared approach to managing WZAD to benefit the broad spectrum of potential uses and users, acknowledging ADS as an important use category.

Implementation of this language is occurring through the WZDx in the Intelligent Transportation System Joint Program Office. WZDx is a publicly available work zone data specification[31] intended to jump-start voluntary adoption of a common data language by data producers and users across the country. Using WZDI to determine agency-specific needs and uses for work zone data, and subsequently developing a customized specification using the WZDx, there will be standardization for data sharing across organizational and geographical boundaries. The WZDx specification enables IOOs to make harmonized work zone data available for third-party use. The intent is to make travel on public roads safer and more efficient through ubiquitous access to WZAD. Specifically, the project aims to get data on work zones into vehicles to help ADS and human drivers navigate more safely.

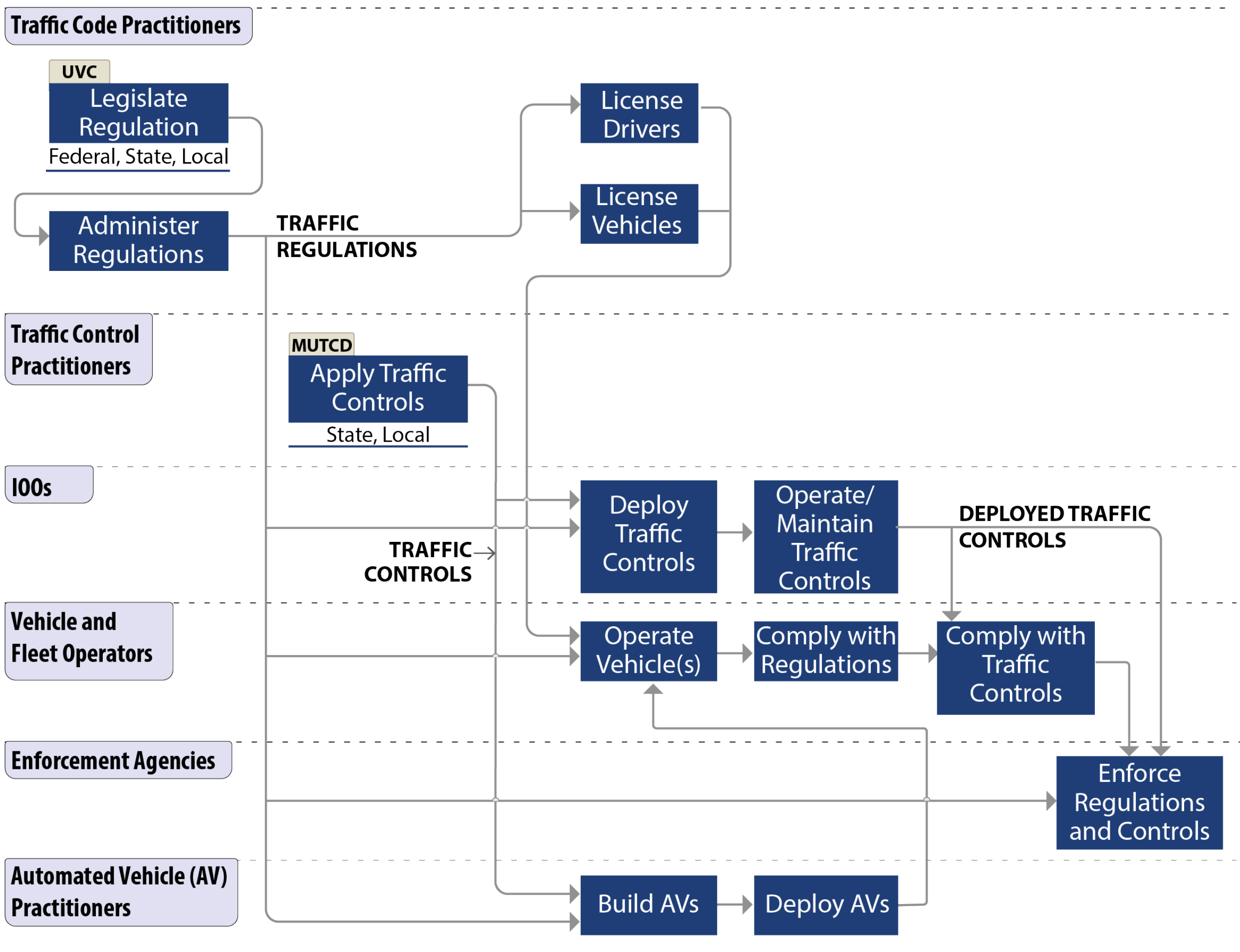
OPERATIONAL OBJECTIVES (JUSTIFICATION FOR CHANGES)

Emerging System Needs

Developers of ADS and associated technologies want, and will eventually need, their products to work seamlessly across the Nation. The deployment of AVs will not happen everywhere at the same time, and the evolution of AVs over time will achieve higher levels of automation across more ODDs. In the meantime, AVs will occupy roadways with human-driven vehicles and be subject to the same traffic regulations and controls, or perhaps even more restrictive regulations designed to limit conflicts with human drivers and other road users.

There is significant diversity of traffic regulations, controls, customs, and enforcement across the Nation. The fundamentals of the driving tasks and maneuvers are necessarily consistent, but the constraints on particular movements may vary. This variation has to do with how traffic regulations are created, administered, applied in design, applied in practice, and enforced in different jurisdictions. Figure 4 depicts this process in terms of traffic regulations, stakeholder actions, and the flow of regulation information.

[31]GitHub, Inc. 2022. "Work Zone Data Exchange (WZDx) Specification" (web page). https://github.com/usdot-jpo-ode/jpo-wzdx/blob/master/README.md, last accessed December 16, 2022.



IOOs = Infrastructure Owner Operators; MUTCD = *Manual on Uniform Traffic Control Devices*; UVC = *Uniform Vehicle Code*.

Source: Federal Highway Administration.

Figure 4. Diagram. Traffic regulation and AV interactions.

Stakeholders in traffic regulations interact with those regulations in roles ranging from legislators and their assistants who draft and enact traffic laws to those who enforce and adjudicate the laws as they are applied to traffic events and circumstances on the roadways. These roles are listed on the left side of figure 4:

- Traffic code practitioners include legislators and support staff, with input from commercial interests and the public. Licensing and administration authorities need to provide expectations for human drivers and ADS operations within their jurisdictions.
- Traffic control practitioners are those who apply uniform descriptions of traffic control devices in subsequent traffic control device deployments on roadways. These developers include civil engineers, planners, and human factors specialists with knowledge of traffic management strategies and techniques and driver and vehicle behaviors.

- IOOs are responsible for deploying, operating, and maintaining traffic control devices on the roadways to support human drivers and ADS.

- Vehicle and fleet operators plan trips, routes, and vehicle movements as they operate vehicles on the roadways.

- Enforcement agencies enforce compliance with the applicable regulations and traffic controls. In this context, the group can be extended to adjudication of traffic regulations in particular instances as played out in the courts and legal system. These stakeholders need to understand the implications of AVs within the traffic flow and be prepared to interact with them appropriately.

- AV and ADS developers are those who are developing the hardware and software systems that will enable vehicles to operate without human drivers in an increasing range of ODDs.

The rectangles in figure 4 represent activities undertaken by traffic regulation stakeholders to ensure that vehicles and their drivers operate safely and effectively. The UVC and MUTCD boxes in figure 4 represent standard forms of traffic regulations and controls in the current world of human-driven vehicles, and as they will need to exist in a world of ADS and AV.

Legislators and their staff with input from transportation agencies, and to some extent private commercial entities and the public, create and enact traffic regulations at the Federal,[32] State, and local government levels. Once enacted, other State and local agencies—such as departments of transportation, departments of motor vehicles, driver license bureaus, and State highway patrol and police—administer regulations. These groups also license drivers and vehicles for those jurisdictions in which the drivers will be operating.

Development of traffic controls renders the intent of legislated traffic regulations into forms that can be localized to the roadway for driver instructions and constraints on vehicle behavior. Each body of traffic regulations needs a set of traffic controls to be developed and applied within its jurisdiction. Once the traffic control devices are defined, they need to be deployed to the roadways as applicable to the particular context for which the control is designed. Dynamic traffic controls, such as traffic signal systems, need to be configured and operated to manage local traffic flow and safety conditions. Static and dynamic controls need to be maintained such that they are visible and actionable by drivers and vehicles.

Licensed drivers are legally enabled to operate licensed vehicles on the roadways. These operations are to be compliant with traffic regulations (i.e., the body of traffic law applicable within the jurisdiction in which the vehicle is operated) and the local traffic controls. This is an important distinction, in that regulations are in practice implicit to those operations and may not be locally marked or signed. Regulations of this type might include speed limits on particular roadway classifications where not otherwise posted, right turns being permissible on a steady red signal, or move-over laws when law enforcement and emergency workers are present. Vehicle

[32]An example of Federal traffic regulations is *Parks, Forests, and Public Property*, 36 CFR §4: *Vehicles and Traffic Safety*.

operations are also generally subject to local custom, in which actions are based on standards of reasonableness or implicit negotiation between vehicle operators.

Law enforcement operates explicitly on the roadways and in the legal systems. Enforcement may be by State and local police and patrols, or by automated means in some jurisdictions. The application of traffic laws may need adjudication in the legal system when the laws depend on standards of reasonableness or operator judgment.

The *UVC* provides a set of traffic regulations on which State and local traffic codes may be based. Traffic regulations are the rules of the road as detailed in the State and local statutes that describe the legal objectives and obligations, the operational requirements, and the consequences of violations.

The *MUTCD* is the national standard for traffic control devices including pavement markings, traffic signals, and signage on roadways. State and local agencies often use traffic control devices in conjunction with the development and application of traffic control regulations.

The types of regulatory pavement markings and signs on the roadways represent the traffic regulations that are in effect to ensure safety and preserve mobility in traffic movement. The application of traffic control devices is based on the roadway design as determined by an engineer (traffic control practitioner) using the *MUTCD* with State and local variations.

User Perspectives and Needs

Each stakeholder group involved in the development and application of traffic regulations brings a different perspective to the needs for a regulations data framework. Individuals from across those groups were interviewed to solicit and clarify their perspectives on the process, nature of regulations data, and potential interactions with the framework. Key concepts and needs identified in those interviews are captured in this section. Many interviews provided insightful observations that ended with questions about how issues might unfold with ADS development and deployment.

Traffic Code Practitioners

Traffic code practitioners help prepare and administer traffic regulations. They work with IOOs to implement regulations and deploy traffic controls and with enforcement agencies to ensure drivers comply with regulations. Traffic code practitioners identified few specific needs but did apply caution in the interpretation and application of existing regulations to ADS. Their observations include the following:

- Language matters. Existing regulations may refer to the operator of a vehicle as a person, driver, or operator, but those terms need to be evaluated in context to determine if they apply to ADS. It will be necessary to identify specific actors and actions to infer application.

- Standards for reasonableness are spread throughout traffic law, alongside inexact but commonly understood language expressing the need for caution. These ambiguous phrasings will need interpretation to become applicable to ADS.

- It is sometimes acceptable in practice to not obey traffic laws—for example, in moving past an incident. These behaviors are generally determined by collective action or by local direction from law enforcement and emergency services. It is unclear how that would be arranged for ADS.

- Legal cases and review are part of building the body of law. Case law does not always result in changes to the enacted legislation. It is unclear how interpretations in case law would be captured for a regulations framework.

- Traffic laws can sometimes be ambiguous and lack a standard of reasonableness that circumvents translation to a digital format. Behaviors in these situations have unknown implications for AVs. Human drivers use customs and negotiation to navigate these circumstances, but ADS may default to behaviors that conservatively interpret regulations and violate local customs.

- Human drivers may use hand gestures and facial expressions to negotiate movements with other drivers. How will those interactions be facilitated among AVs and human drivers, or simply among AVs?

Traffic Control Practitioners

Traffic control practitioners as a stakeholder group develop or apply standards for traffic control devices installed on any street, highway, bikeway, or private road open to public travel. This is an important, and largely uncontroversial, part of implementing the rules of the road, but the manner in which it develops has implications for a regulations data framework. Comments in interviews included the following:

- The current edition of the *MUTCD* was issued in 2009—with traffic control devices installed in the field representing devices from the current edition. Future editions of the MUTCD are likely to include new innovations that would take time to be widely implemented. Traffic control devices for bicycles and work zones are among the greatest areas of *MUTCD* experimentation.

- Options are provided in the *MUTCD* to allow flexibility for design and local custom. This variability may factor into State and local preferences for particular implementations, which are then encoded in traffic laws for those States and localities. These preferences then become the basis for and cause of traffic control diversity across the country. As a result, it will be necessary to go to every State (and potentially local agency) to identify controls specific to those jurisdictions.

IOOs

IOOs include State and local agencies deploying, operating, and maintaining traffic control devices in fulfillment of statutes. Most State traffic codes authorize agencies to specify traffic control devices appropriate to their respective States (in their roles as traffic control practitioners), rather than specify the traffic control devices within the statutes. IOOs are responsible for deploying those devices on the roadways, operating the dynamic devices such as traffic signals and ramp meters, and maintaining the devices. IOOs support enforcement agencies in ensuring that drivers comply with the regulations. Observations from the interviews included the following:

- The unstated presumption on traffic control devices appeared to be that pavement markings and signs would need to continue to be deployed indefinitely for human drivers and ADS. It was acknowledged that some changes in deployment and maintenance might need to be made to accommodate ADS sensing and perception subsystems—for example, restriping roadways with wider stripes and maintaining an acceptable level of reflectivity.
- There was concern that trying to maintain a digital representation of deployed traffic control devices would quickly become untenable. State or local agencies do not always maintain sign databases well, and the number of traffic signs is higher than generally appreciated.
- IOOs also noted that deployment of traffic control devices can create conflicts between jurisdictions over control and standards. Such situations can arise, for example, on State routes through municipalities where varying traffic control device preferences or standards are being deployed. Such issues with jurisdictional control may be referred to courts for adjudication.

Vehicle and Fleet Operators

Vehicle operators are key stakeholders in ensuring compliance with traffic regulations as vehicles move throughout the roadway network. This responsibility falls to individual drivers, and to a lesser extent dispatchers and managers of fleets of vehicles. Human drivers will continue to have this responsibility even with the development and deployment of advanced driver assistance systems through SAE Level 3, and for ODDs not explicitly automated at SAE Level 4. ADS-equipped vehicles operating at SAE Level 4 and SAE Level 5 will fully subsume this responsibility for their designated ODDs.

Enforcement Agencies

Enforcement agencies monitor roadways for violations and adjudicate perceived violations in the traffic courts. Municipal police forces, sheriff departments, and State police or highway patrol generally enforce roadway traffic laws. Some locations have enacted automated enforcement, such as red-light cameras and safety speed cameras, some of which provide only warnings and some of which issue citations for violations.

Interviewees noted that enforcement of traffic laws with AVs and all levels of driving automation is a subject of intense interest among agencies. The American Association of Motor Vehicle Administrators has issued initial information on the subject and continues to be in conversation with ADS developers. Current topics of interest include whether AVs should provide an indication external to the vehicle that an ADS is operating. This type of indication would help enforcement officers in knowing how to approach a vehicle in violation of a traffic rule. Key considerations for the purposes of the regulations framework are that enforcement actions and traffic case law may need to be included in the framework when enforcement agencies accumulate experience with AVs and potential violations.

ADS Developers

ADS developers are researchers and programmers working on behalf of academic institutions, governmental agencies, technology companies, and vehicle manufacturers involved in ADS development. Within this community there is tremendous diversity of interest in and approaches to ADS development. The sample of interviews conducted for this study ranged from startup technology companies to large multinationals, and from tier-one suppliers to light- and heavy-vehicle manufacturers. All interviewees were clear about needing reliable, consistent regulatory data in support of ADS development.

ADS developers consistently expressed concerns about the diversity of regulations among jurisdictions, especially with regard to the letter of the law, and the need for a precise understanding of its intent for each jurisdiction. This leads to potential conflict for ADS behavior. The developers prefer a harmonized understanding of traffic regulations across jurisdictions to develop consistent behavioral algorithms. This was usually expressed during interviews in descriptions of specific ODD challenges and the impact of regulation diversity on those instances—for example, in passing regulations and keeping right; letting others pass; four-way, stop-sign-controlled intersections; or entering an intersection on a yellow traffic signal.

The consistent concern about diversity and complexity of regulations may be a significant limitation on the ODDs for which automation is developed, at least in the near term. ODDs do not necessarily line up with the manner in which the regulations were enacted. The regulations were set up for human drivers based on situations drivers would encounter along the roadways. Thus far, individual ADS development teams have identified and described ODDs based on their business plans and needs. There does not appear to be any particular regard for standard or systematic ways of ensuring that all regulations, use cases, and development needs would eventually be addressed. One interviewee suggested that traffic laws can be considered part of the ODDs themselves, implying a level of complexity in ODDs similar to that in the regulations. As such, ODDs may be limited in the near term to those with the fewest or least complex regulations, or at least those with the most specific rules.

Another common discussion was how regulations that presume a human vehicle operator might apply to ADS-equipped vehicles. This seemed to be a greater concern for ADS-equipped heavy vehicles—for example, laws about putting reflective triangles on the roadway behind disabled vehicles.

Interviewees expressed mixed perspectives on whether regulations information should reside onboard the vehicle, presumably encoded as algorithms, or be made available from a data cloud over a vehicle-to-infrastructure (V2I) connection. Some envisioned a regulations service similar to a map service, but all observed that vehicles will need to be able to operate without connections, at least for some period of time, especially in rural areas.

There seemed to be distinct perspectives on development for light vehicles and for heavy vehicles. This may be due in part to the Federal regulations on heavy-vehicle operations (related in turn to regulation of interstate commerce). There may need to be an assessment of the interfaces between traffic regulations and permitting heavy vehicles that will affect routing and operations across or around their ODDs.

One interviewee summarized ADS developer concerns with traffic regulations as being a significant part of their greater concern with a need for standardization and information on testing and certification of ADS behavior for the intended ODDs.

SYSTEM CONCEPTS AND ARCHITECTURE

Traffic Regulations Data and the *UVC*

Although the *UVC* is not prescriptive for traffic regulations across the United States, it is archetypical and can be used to identify the fundamental elements of traffic control regulations. Chapter 1[33] of the *UVC* defines words and phrases for transportation system users, vehicle types, roadway types, and other elements used in the regulations. Chapter 11, "Rules of the Road,"[34] describes the regulations for the interactions of road users with each other, the roadway, and the flow of traffic. Intended readers are human drivers, regulators, administrators, and enforcement officers, so the regulations implicitly describe the interactions between those user roles. The regulations are expressed in text and, in most cases, rely on subjective measures of caution or safety. Many of these regulations provide constraints on driver and vehicle behaviors, but these constraints are seldom specific or measurable.

For example, Section 11–310, "Following too closely," states, in part, "[t]he driver of a vehicle shall not follow another vehicle more closely than is reasonable and prudent, having due regard for the speed of such vehicles and the traffic upon and the condition of the highway."[35]

The *UVC* does not provide interpretations of or measurable values for "more closely than is reasonable and prudent" or "due regard for the speed of such vehicles." As such, the *UVC* and similar traffic codes are not directly reducible to algorithmic expression. They may be interpretable as such where they are supported or extended to include specific operational performance measures.

Traffic Regulation Data Elements and Definitions

Figure 5 depicts entities and relationships involved in regulating ADS. This section describes the entities and the interrelationships among them.

State and local government entities enact and enforce traffic statutes. As IOOs, they interpret traffic regulations and deploy traffic control signals and signs. State and local governments have jurisdictions defined by geographical boundaries and enact statutes that can be interpreted as

[33] NCUTLO. 2000. "Chapter 1—Words and Phrases Defined," in *Uniform Vehicle Code*. Alexandria, VA: NCUTLO.

[34] NCUTLO. 2000. "Chapter 11—Rules of the Road," in *Uniform Vehicle Code*. Alexandria, VA: NCUTLO.

[35] NCUTLO. 2000. *Uniform Vehicle Code*. Alexandria, VA: NCUTLO, 134.

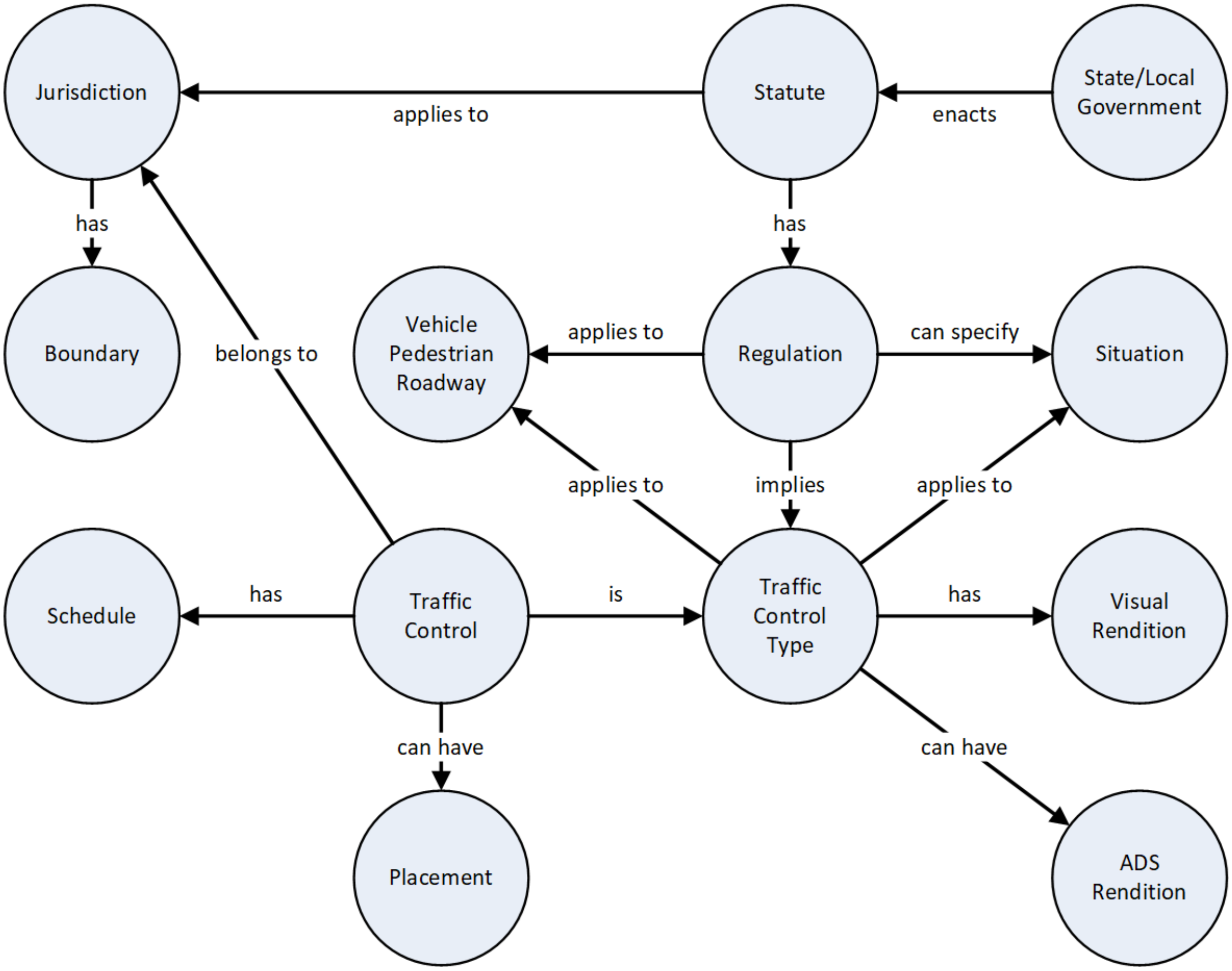
regulations. A jurisdiction is a specific region over which government and IOOs have authority. It determines the area within which statutes and regulations apply, and it is defined by one or more boundaries. A boundary encloses a jurisdiction and is defined by a set of geocoordinates. Boundaries are generally shared with adjacent jurisdictions, and a particular location may be contained within more than one boundary (e.g., within a municipality, a county, and a State). A statute is an element of law that a legislative body enacts to set forth general propositions that can be applied to specified situations.

Regulations can help inform the traffic control types, but the behaviors that result from the traffic controls are sometimes not explicitly stated in the associated regulations. However, not all regulations applicable to vehicles and their operation necessarily imply a related traffic control type. For example, the length that externally carried cargo can protrude to the front or rear of a vehicle may be regulated but does not constitute a traffic control.

Here are the key nodes:

1. **Traffic Control**: Central node, connected to other nodes.
2. **Jurisdiction**: Connected to "Statute" and "State/Local Government."
3. **Statute**: Enacts regulations.
4. **State/Local Government**: Governs traffic control.
5. **Vehicle Roadway**: Belongs to jurisdiction.
6. **Pedestrian Boundary**: Applies to regulation.
7. **Traffic Situation**: Has visual control.
8. **Roadway Placement**: Can specify traffic control.
9. **ADS Rendition**: Related to placement.

The arrows indicate relationships like "applies to," "has," or "can specify." Overall, it seems to depict how traffic control measures are determined within legal frameworks.



Source: Federal Highway Administration.

Figure 5. Illustration. Automated driving system regulations data concepts.

The *MUTCD*[36] is the national standard for traffic control devices. Traffic control types apply to classes of transportation infrastructure users and facilities and enable or restrict maneuvers. Traffic control types specify the classes of controls that may be deployed within a jurisdiction to enact the regulations. Traffic control types define constraints on driving behavior, such as maximum speed for commercial tractor/trailers. Traffic control types are associated with visual renditions such as signage graphics and striping; frequently limit direction of movement; and apply to various classifications of vehicles, roadways, and pedestrians. Traffic control types may also include a human controlling traffic, such as a police officer, school crossing guard, or person providing traffic control for a work zone.

A visual rendition is a set of geometric parameters and styling (e.g., shape, color, size) that describes how a traffic control will be visibly presented based on the *MUTCD*. Graphical

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

elements typically use vector parameters to define size and location within the rendition so that they are easy to scale and transform into different contexts.

Traffic controls for ADS may also be deployed as a set of logical components, referred to here as the ADS rendition. Vehicles, pedestrians, and roadways refer to classes of transportation infrastructure users and types. Familiar vehicle classes include passenger car, bicycle, motorcycle, bus, and commercial tractor/trailer. Pedestrian classes include people in general, schoolchildren, and people who have physical disabilities. Roadway classes include freeways, highways, arterials, and neighborhood roads.

Situations in the traffic regulations describe maneuvers (longitudinal and lateral vehicular movements) such as passing, stopping, merging, and turning at intersections. Regulations can allow, disallow, or constrain maneuvers under particular situations.

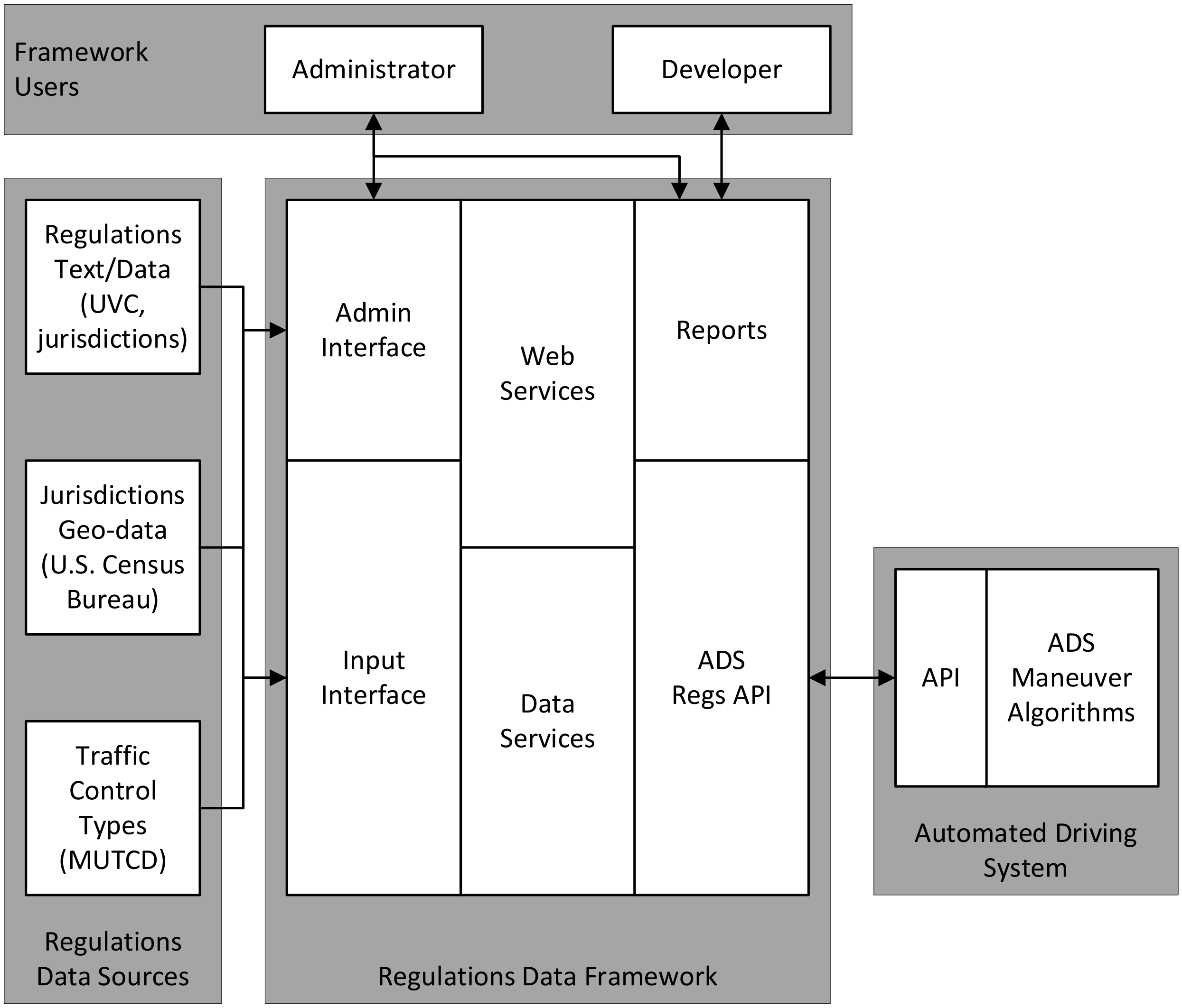
Traffic controls are instances of traffic control types deployed to particular locations on the roadway network. Traditional traffic controls typically involve visual markings, signs, and signals. Traffic controls inherit the properties of traffic control types, including visual and ADS renditions. The traffic controls may have times during which they are in effect and specific physical locations. Many traffic control instances can be created from a few traffic control types.

Each traffic control has a schedule during which it is active. Schedules may represent continuous application, specific days and hours of operation, or cycles of operation (e.g., traffic signal and ramp meters). For example, the schedule for a maximum speed allowed in a school zone could be as complex as weekdays between 2 and 4 p.m. from the start to end dates of the jurisdiction's school year.

Placement describes the physical location (i.e., longitude, latitude, height above grade) and orientation (which direction a sign faces) of a traffic control. If a traffic control does not have a specific placement, it may apply within a jurisdiction's boundaries as a policy. For example, U-turns may be prohibited within a jurisdiction regardless of whether a sign is placed at an intersection.

Prototype Traffic Regulation Interfaces

Based on the stakeholder needs and use cases, the prototype system concept enables storage and retrieval of regulations, situations associated with regulations, traffic control types, and deployed traffic controls. Interfaces are needed for human administrator users representing the stakeholder groups, for developers, for ADS and other systems using the regulations data, and potentially for existing sources of digital regulations data. A secure web browser application is used for the human administrator users. A web browser application enables the interface to be developed and distributed with low-cost tools and relatively high assurance of user access and acceptance. Figure 6 illustrates the conceptual relationships among users, data sources, framework components, and ADS.



Source: Federal Highway Administration.

ADS = automated driving system; API = application programming interface; *UVC* = *Uniform Vehicle Code*.

Figure 6. Illustration. Regulations data framework and interfaces.

An interface using standard web-based request-response patterns will similarly provide access to digital interpretations of regulations for ADS and other systems. Interfaces for existing sources of online regulations data may be provided where the development effort can be leveraged to multiple sources or be reused to update the regulations data on a regular basis.

Populating the data elements of this model involves cataloging and interpreting the regulations. Some of the data needed for enabling development and operations of the regulations data framework and interfaces are readily available from authoritative sources. The U.S. Census Bureau publishes the legal boundaries and names of jurisdictions, and the related Federal Information Processing Standards, Zone Improvement Plan, and geocoordinate boundaries in shape file format. FHWA publishes visual representations of signs from the *MUTCD* as downloadable Encapsulated PostScript and PDF files. Pedestrian, vehicle, and roadway classifications and allowed maneuvers can also be derived from State or local regulations in conjunction with published Government standards.

Regulations data exist in digital forms ranging from scanned paper and merged-text documents to elemental and combined PDF documents and Hypertext Markup Language snippets. Whether implemented as a dedicated software interface or through a human system administrator, a regulations ingest interface will record the jurisdiction associated with the data, a source reference, available reference numbering and labels, and, optionally, the regulatory text itself. An interpretive process for regulations is likely performed by a qualified human analyst, and fulfilled through associating each regulation with application actor classifications (pedestrians, vehicles, roadways) and maneuvers chosen from lists set up in the system library.

The administrator interface will include a means to configure traffic control types, with a related interface to configure traffic control instances based on those types. Each traffic control type will have a unique identifier and name, an optional expanded description, associations with related regulations, associations with actor classification and maneuvers, and visual representations from the *MUTCD*. The traffic control data will generate ADS renditions.

Each traffic control instance will have a unique identifier and reference the traffic control type on which it is based. Traffic control instances will have a default continuous schedule that can be overridden with flexible day-of-week, affected hours, and repeating intervals. Traffic control placement will consist of latitude, longitude, elevation, and orientation and applicable approach vectors.

Output interfaces for ADS and other systems will be selected based on a jurisdiction or geocoordinate region. The output will be in a common data exchange format, such as JavaScript Object Notation (JSON) or eXtensible Markup Language.

Even a sparsely populated ADS regulation data framework provides a basis for AV-related information. The prototype application can be used to select a jurisdiction and view a list of regulations and corresponding interpretations, a list of traffic control types and visual presentations, or a list of traffic control instances and locations. Report views can be exported to a text file format, such as a comma-separated values (CSV) format. External software systems, such as AV fleet managers or AVs, can request the same information as human users.

Applicable Standards

Specification of traffic regulations information does not explicitly appear in any of the common ITS standards. There do not appear to be any broadly applicable standards for interfaces to regulations or statutes beyond the common legal language and forms. The *MUTCD* is the most explicit example of a standard specifying information related to traffic control devices. The *MUTCD* (or a State-specific version) is specified in all State codes as the basis for standard traffic controls.[37]

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[37] *Highways*, 23 CFR §655.603: *Standards*.

Some data elements related to traffic controls—for example, regulatory speed limits—may otherwise be specified in ITS standards, such as the Traffic Management Data Dictionary[38] and National Transportation Communications for ITS Protocol (NTCIP). NTCIP 1202, *Object Definitions for Actuated Signals Controllers (ASC) Interface*[39], for example, includes speed limit data elements but does not reference any regulatory basis. Some control-related data elements are also specified in the SAE J2735™[40] and SAE J2945™[41] series for connected vehicle data definitions and messaging.

USE CASES AND ODDS

Use cases describe the applications and interactions of stakeholders with the prototype framework, including its relationship to potential ODDs for the ADS-equipped vehicles. Use cases address perspectives of specific stakeholder groups (e.g., ADS developers, regulators) as they relate to the system being described or developed. In this case, there are at least two possible views of the system. The most specific view is that the system in question is the data framework for traffic regulations. That may be insufficient to meet the implied intent of the framework, which is to provide ADS developers with a view of traffic regulations that will be useful in development and deployment of AVs. A more nuanced view of the potential use cases has (at least) two layers: 1) use cases for the framework itself, addressing the perspectives of providers and users of the regulations data and 2) use cases for the regulations data within the framework, focused on the needs of ADS developers. Use cases for the framework are conditional on use cases for the regulations data. If the data and the way they are represented are not useful in ADS development and operations, the framework itself may not be useful.

The ongoing evolution of ADS and the AV ecosystem suggests a phased approach to the capture, management, and provision of regulations data:

- Early-stage ADS and AV development is focused on research and demonstration in ODDs the developers select. These ODDs are necessarily constrained so that developers can successfully demonstrate automated operations. As such, the ODDs are limited to particular classes of roadways, interactions with other vehicles and other users, and jurisdictions. Developers need to know only the regulations that apply to those particular contexts. It is probably sufficient in this phase to focus on use cases related to capture of and access to enacted traffic regulations for jurisdictions in which the ADS intends to be operating.

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[38] Institute of Transportation Engineers (ITE). 2020. "Traffic Management Data Dictionary (TMDD) Standard v3.1 for the Center-to-Center Communications." Washington, DC: ITE.

[39] AASHTO/ITE/National Electrical Manufacturers Association (NEMA). 2019. *National Transportation Communications for ITS Protocol: Object Definitions for Actuated Signal Controllers (ASC) Interface*. NTCIP 1202 v03A. Washington, DC: AASHTO; Washington, DC: ITE; Rosslyn, VA: NEMA. https://www.ntcip.org/file/2019/07/NTCIP-1202v0328A.pdf, last accessed December 19, 2022.

[40] SAE International. 2020. *V2X Communications Message Set Dictionary*. SAE J2735_202007. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2735_202007/, last accessed December 19, 2022.

[41] SAE International. 2017. *Dedicated Short Range Communication (DSRC) Systems Engineering Process Guidance for SAE J2945/X Documents and Common Design Concepts™*. SAE J2945_201712. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2945_201712/, last accessed December 19, 2022.

- Traffic controls point to traffic regulations as they apply on the roadways. ADS operations on public roadways will need to have sufficient awareness of traffic controls to limit those operations to the ODDs for which they are designed. Adding traffic control types to be expected in particular jurisdictions expands the regulations framework so that potential ADS deployments have access to a library of traffic controls they might encounter and need to understand in those jurisdictions. This library serves as a reference for further expansion of ODDs to include a broader range of maneuvers and control types.

- There was a diversity of opinion among interviewed stakeholders as to how regulations (and updates to them) might be provided to AVs. The consensus was that an ADS would need to be able to depend on its sensors to identify deployed traffic controls, but there was a parallel awareness that traffic control locations might also be digitally mapped and provided to ADS-equipped vehicles. This is not a novel idea; it is the concept behind the MAP and signal phase and timing messages defined in SAE J2735™[42] for V2I messaging. Mapping deployed traffic controls, especially where the control state or parameter is variable—for example, at traffic signals or with variable speed limits—enables the regulations framework to provide dynamic as well as static regulations data.

- Traffic statutes as written and enacted in the State and local traffic codes use human language to describe the intent of the statutes. Interpreting those regulations for an ADS must render the intent into instruction based on actors, actions (or maneuvers), and constraints on those actions. The most direct implementation of those interpretations is to hard code the rules of maneuvers needed for the ADS ODDs into the ADS. Much of the concern around variability in traffic regulations derives from the lack of scalability in this approach. It is prescriptive rather than adaptive. Moving beyond this type of implementation will require a data-based representation of the regulation. That interpretative component or database might reside onboard the vehicle, but it could be part of the regulatory framework.

Framework Use Cases

The framework-level use cases describe the interactions with the framework as a whole and may be specific to particular groups of stakeholders. The use case descriptions are intended to be functional and are not meant to imply particular prototype implementations.

Provide Regulations

The regulations framework will respond to a request for regulations with the text of traffic regulations based on jurisdiction or location. Requests are anticipated to come from human ADS developers. As a precondition, the text will have been loaded into the framework with its associated jurisdiction, statutory references, and dates of applicability (if appropriate). The response will result in a text report of the regulations being provided to the requestor.

[42]SAE International. 2020. *V2X Communications Message Set Dictionary*. SAE J2735_202007. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2735_202007/, last accessed December 19, 2022.

Provide Traffic Control Types

The regulations framework will respond to a request for potentially applicable traffic controls with the names of the control types, the *MUTCD* or State and local references, and marking/sign images based on jurisdiction or location. Requests are anticipated to come from human ADS developers. As a precondition, the traffic controls will have been loaded into the framework with associated jurisdiction, references, images, and dates of applicability (if appropriate). The response will result in a text report and graphics files for the traffic control types being provided to the requestor.

Provide Deployed Traffic Controls

The regulations framework will respond to a request for deployed traffic control devices with the names of the deployed traffic control devices, *MUTCD* or State and local references, and specific location and attributes based on jurisdiction or general location. Requests are anticipated to come from automated systems, or ADS developers using a manual command. As a precondition, the deployed traffic control devices will have been loaded into the framework with associated types, locations, and dates of applicability (if appropriate). The response will result in a text report and graphics files for the traffic control types being provided to the requestor.

Provide Interpreted Regulations

The regulations framework will respond to a request for interpreted regulations with data describing maneuvers, actors, and applicable constraints equivalent to regulations within a jurisdiction or applicable at a location. Requests are anticipated to come from automated systems. As a precondition, the regulation will have been interpreted and loaded into the framework with its associated jurisdiction, statutory references, and dates of applicability (if appropriate). The response will result in digital representation of the regulation being provided to the requestor.

ADS Development Use Cases

The fundamental question for use cases to address is how the regulations framework can inform and represent regulatory constraints on ADS behavior in traffic. The regulations themselves were set up for human drivers based on situations that drivers would be encountering as they proceed along the roadways. To that extent, the regulations generally align with use cases for driver behavior. However, the use cases approached in this way do not necessarily line up with the concept of ODDs. Thus far, individual ADS development teams have identified and described ODDs without particular regard to standard or systematic ways of assuring they would eventually address all regulations, use cases, and development needs. In light of this, the most scalable approach is to consider use cases based on regulations in the definition and scoping of ODDs as they are developed.

It is then reasonable from a regulatory perspective to define use cases for ADS development based on the actors and actions (or maneuvers) described in the regulations themselves. Although the regulations vary among State and local traffic codes, the fundamental driving behaviors are substantially the same. Variability among traffic codes in the United States lies primarily in the extents and limits placed on maneuvers, not the mechanics. Making a right turn at a signalized intersection is fundamentally the same driving task regardless of whether the maneuver takes place for example in Connecticut or California. The regulatory differences (if any) lie in the circumstances and constraints under which that right turn is allowed.

Since there is generally structural agreement among the various traffic codes on the descriptions of maneuvers, it is reasonable to use the *UVC* as a basis for identifying the ADS development use cases for the regulatory data framework. Variability in the traffic codes for particular use cases would then be parameterized to capture the jurisdictional differences. Table 1 suggests classes of use cases based on the sections (articles) in chapter 11[43] of the *UVC*.

Table 1. Classes of use case based on the *Uniform Vehicle Code* (*UVC*).

Potential Classes of Use Cases [with *UVC* Section Title]	References
General Traffic Reg Compliance [Obedience to and Effect of Traffic Laws]	*UVC* Ch. 11 Article I
Interpretation of and Compliance to Traffic Controls [Traffic Control Devices]	*UVC* Ch. 11 Article II, *MUTCD*
Work Zones	*MUTCD*
Incidents and Emergency Operations	*UVC* Ch. 11 various articles
Highways [Driving on Right Side of Roadway – Overtaking and Passing – Use of Roadway]	*UVC* Ch. 11 Article III
Intersections [Right -of-way]	*UVC* Ch. 11 Article IV
Intersections [Turning and Starting and Signals on Stopping and Turning]	*UVC* Ch. 11 Article VI
Special Stops Required	*UVC* Ch. 11 Article VII
Speed Restrictions	*UVC* Ch. 11 Article VIII
Stopping, Standing, and Parking	*UVC* Ch. 11 Article X
Miscellaneous Rules	*UVC* Ch. 11 Article XI
Faulted Operations [DUI and other Serious Traffic Offenses]	*UVC* Ch. 11 Article IX
Pedestrians' Rights and Duties	*UVC* Ch. 11 Article V

Ch. = chapter; DUI = driving under the influence; *MUTCD = Manual on Uniform Traffic Control Devices*.

A complete list of ADS development use cases based on the *UVC* and its State and local variations would entail a review of all those traffic codes to identify degrees of variability and edge cases. As that type of review is beyond the scope of this study, typical cases that might be used in demonstrating the framework are suggested here. The emphasis is nonetheless on cases that need data that vary among jurisdictions. The focus of the use case is on the availability of traffic regulation and control data to the ADS, not on the design or implementation of algorithms within the ADS.

There are two key questions: 1) Can the ADS determine constraints on maneuvers (regulations) applicable to the jurisdiction in which it is operating at the moment of decision? 2) Can the ADS recognize the traffic controls it encounters in its local operations? These and other similar

[43]NCUTLO. 2000. "Chapter 11—Rules of the Road," in *Uniform Vehicle Code*. Alexandria, VA: NCUTLO.

questions will become part of the basis for the POC demonstration and the framework testing plan.

Comply With Speed Limits

An ADS-equipped vehicle moves along a roadway with no apparent local indication of the speed limit and crosses the boundary with an adjacent jurisdiction, also without a posted speed limit. The ADS will have a local database of speed limits for the jurisdictions in which it expects to operate or will have remote access to a service providing the speed limit data. As the vehicle approaches the boundary, the ADS will query the database to determine the speed limit with which it needs to comply. The ADS will then change the vehicle speed to remain within the locally applicable limit.

Comply With Left-Turn Controls at Signalized Intersections

An ADS-equipped vehicle approaches a signalized intersection and moves into the left-turn lane. The ADS recognizes the red signal and stops at the stop line. The ADS monitors the signal status and initiates movement through the intersection when allowed by the green left arrow on the signal. It proceeds along that roadway to an intersection coincident with the boundary with an adjacent jurisdiction. The vehicle moves into the left-turn lane. The signal is indicating a flashing amber left-turn arrow. In this use case, the ADS will need to have information and algorithms for left-turn traffic controls in both jurisdictions. The ADS monitors oncoming vehicle and local pedestrian traffic to determine a safe interval for completing the left turn. The vehicle completes its left turn and proceeds along the new roadway.

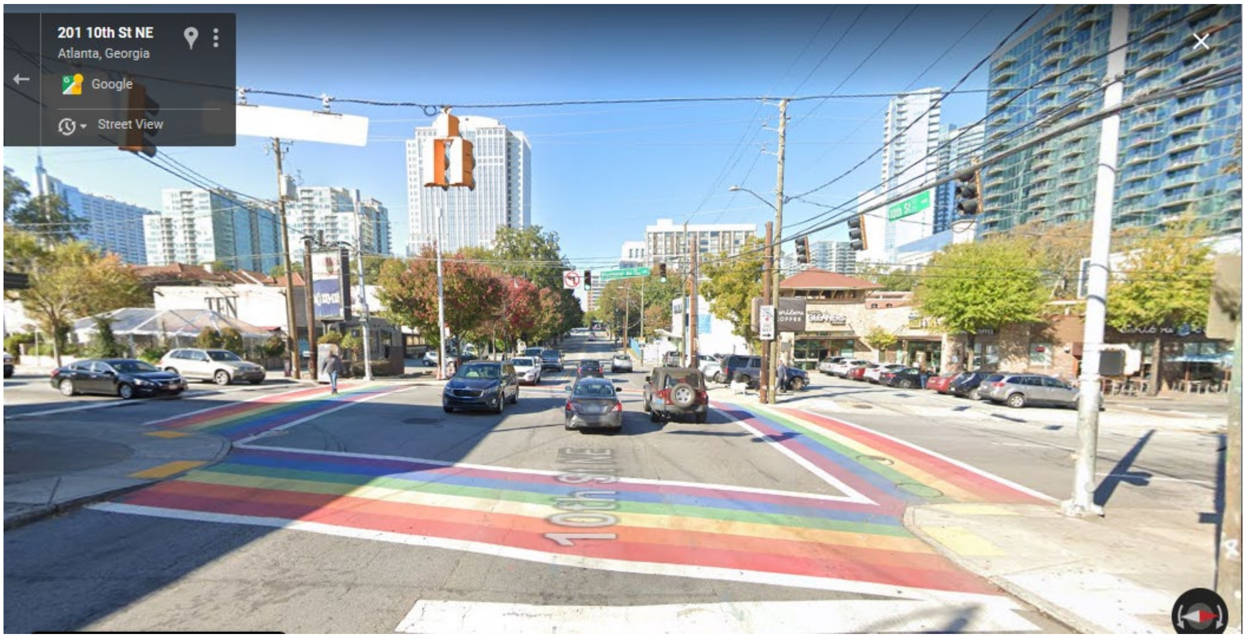
Comply With Right-Turn-on-Red Regulations at Signalized Intersections

An ADS-equipped vehicle approaches a signalized intersection with the intent of turning right. The signal is red, and the vehicle stops at the stop line. The ADS queries whether a right turn on a red signal is permitted in this jurisdiction. There is no sign indicating that a right turn on red is not permitted at this location. If the right turn on red is permitted, the ADS monitors oncoming vehicle and local pedestrian traffic to determine a safe interval for completing the right turn. The vehicle completes its turn and proceeds along the new roadway.

As a variant use case, the ADS-equipped vehicle will approach a signalized intersection where right turn on red is not permitted, as signed at the intersection. The ADS monitors the traffic signal, oncoming vehicles, and local pedestrian traffic to determine a safe interval for completing the right turn. The vehicle completes its turn and proceeds along the new roadway.

Identify and Comply With Nonstandard Pedestrian Crosswalk

An ADS-equipped vehicle approaches a signalized intersection with the intent of turning right at the intersection. The signal is red, and the vehicle stops at the stop line. The pedestrian crosswalk does not have the standard pavement markings or pedestrian crossing signs expected for this jurisdiction (figure 7). The ADS must monitor the traffic signal, vehicle cross traffic, and the atypical presence of pedestrians to determine a safe interval for completing the right turn. The vehicle completes its turn and proceeds along the new roadway.



Source: Google® Maps™.

Figure 7. Screen capture. Nonstandard pedestrian crosswalk in Atlanta, GA.

Comply With Nonspecific Headway Regulations on Highway

An ADS-equipped vehicle is moving along a highway and approaches a vehicle ahead of it that is moving more slowly. There is no opportunity to legally pass the slow vehicle on the left (or right). The local regulations do not specify a minimum following distance or time interval. Due to the subjective nature of safe following distance, a law enforcement officer could pull over an ADS if the officer determines the following interval set by the ADS's algorithm is too close for conditions.

> *UVC* 2000 Section 11–310(a):
>
> *"The driver of a vehicle shall not follow another vehicle more closely than is reasonable and prudent, having due regard for the speed of such vehicles and the traffic upon and the condition of the highway."*[35]

Comply With Regulations on School Bus Interactions

An AV is moving along a single-lane highway and approaches a school bus ahead of it that is stopped in the lane. The ADS does not detect any pedestrians in its path or along the edges of the roadway. The ADS queries its regulations database to determine the constraints on its maneuvers in the jurisdiction through which it is traveling. Are stop signs extended by the bus? Are flashing red indicators on the bus? Is the ADS required in this jurisdiction to stop behind the bus and proceed only after the bus has moved and no pedestrians are detected? Is the ADS allowed to pass the bus on the left if there are no stop indications on the bus and there are no pedestrians detected?

Applicability to ODD

The Automated Vehicle Safety Consortium (AVSC) provides the basis for the definition of ADS ODDs in *Best Practice for Describing an Operational Design Domain: Conceptual Framework* *and Lexicon*.[44] The concept of an ODD was drawn from prior NHTSA perspectives on voluntary safety self-assessment and ADS testing by the ADS developers and manufacturers. The AVSC document intends to provide a common framework and lexicon for ODDs that can be used to describe the domains for which the ADS are being developed and subsequently tested.

As such, the regulations data framework will provide interfaces to the regulations with which ADS developers can associate their ODDs to identify variations in regulations across jurisdictions. In the prototype demonstrations, the framework was used to provide traffic regulations relative to 1) use of the left-hand lane when driving on a freeway and 2) a right-hand turn after a stop at a red traffic signal. The corresponding ODDs were: 1) a segment of freeway without entrance or exit ramps and 2) a section of arterial network where right-turn-on-red was allowed at some but not all intersections.

As a more extensive example, a developer of an ADS might constrain its ODD for an SAE Level 4 automated freight vehicle to operations along a specific interstate highway route across two States. Use cases supported by the ADS regulations framework and corresponding situations described in the regulations could include:

- Complying with speed limits
- Complying with limitations on the use of the left-hand passing lane
- Complying with nonspecific headway regulations on highways
- Complying with limitations on freight vehicle use of particular lanes

In this example, the ADS must be able to comply with variations in State regulations for those situations when moving from one jurisdiction to the next. The ADS developer will need to identify the particular situations in those two sets of State regulations that apply to its definition of the ODD.

FRAMEWORK CONCEPT FOR OPERATIONS AND MAINTENANCE

The regulations data framework provides a structure for storage and access to traffic regulations data, but acquires the text and attributes of the regulations from other primary sources. As such, operations and maintenance of the framework will need to address governance, investment (or ownership) alternatives, and operations agreements. These operations agreements may need to include the perspectives of stakeholders previously identified and potentially extend to standards development organizations. Stakeholder and user agreements may need to acknowledge the research nature of the traffic regulations data framework pilot and liabilities of using the framework as a basis for assessing compliance with jurisdictional traffic regulations.

Collaborative specification and operations of transportation datasets, standards, and frameworks has taken many forms. Examples include:

- The National Committee on Uniform Traffic Laws and Ordinances (NCUTLO) , made up of representatives of State highway and transportation departments and now defunct, developed the *UVC*. The *UVC* was designed to provide comprehensive information about

[44]SAE International. 2020. *AVSC Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon*. AVSC00002202004. Warrendale, PA: SAE International.

traffic and vehicle codes for States to use as they developed motor vehicle and traffic laws.[45] The *UVC* was last updated in 2000.[46]

- The National Committee on Uniform Traffic Control Devices provides recommendations regarding the content of the *MUTCD*. FHWA drafts and publishes the *MUTCD* in accordance with the Administrative Procedure Act.

- The AASHTO Green Book[47] has its origins in collaborative efforts among State transportation agencies, much like the *UVC* and *MUTCD*. Under 23 U.S.C. 109,[48] the Secretary of Transportation must approve design standards for projects on the national highway system (NHS). FHWA, to which the Secretary has delegated this authority, uses a formal rulemaking process to designate the Green Book as the set of design standards for NHS projects.

- Security credential management system (SCMS) is the result of the recognized need early in the development of connected vehicle technologies for a security infrastructure for V2V and V2I messaging. USDOT initiated and sponsored research into and prototyping of an SCMS in a security credential management system POC the CAMP conducted. The original governance concept envisioned a federated system of certificate management under a root authority and registered certificate authorities. That model has evolved into its own ecosystem of commercial certificate management services providing a security infrastructure that complies with standards originating in the SCMS POC.

A similar range of governance and operations options, based on ownership/sponsorship and service implementation, exists for a traffic regulations data framework for ADS. Options for framework governance could include:

- A federated or distributed service the various State and local governments provide
- A service USDOT or a USDOT contractor operates
- A service a nongovernmental institution or association on behalf of member agencies provides
- A service private operators working to standard interfaces and certifications provide

Agreements between the service provider and each of the traffic regulations data providers may be needed to ensure consistent provision and maintenance of up-to-date traffic regulations. These agreements might need to address provisions for update frequency and latency, accuracy, and enforceability. Providers could include, for example:

- Traffic code practitioners (i.e., State and local agencies, or those acting on their behalf)

[45]FHWA. 2012. *Manual on Uniform Traffic Control Devices* (*MUTCD*). Washington, DC: FHWA. https://mutcd.fhwa.dot.gov/ser-pubs.htm, last accessed December 19, 2022.

[46]NCUTLO. 2000. *Uniform Vehicle Code*. Alexandria, VA: NCUTLO.

[47]AASHTO. 2018. *A Policy on Geometric Design of Highways and Streets*. 7th ed. Washington, DC: AASHTO.

[48]GovInfo. 2015. *23 U.S.C. § 109. Highways*, Washington, DC, obtained from: https://www.govinfo.gov/app/details/USCODE-2021-title23/USCODE-2021-title23-chap1-sec109, last accessed September 25, 2023.

- IOO, as deployers of traffic control devices

Agreement may also be needed between the service provider and each of the potential data users:

- ADS developers, in their applications to driving automation systems
- Vehicle and fleet operators, where the ADS-enabled vehicles need to be assured of access to up-to-date traffic regulations
- Enforcement agencies, for assurance that the regulations as provided are consistent with enforcement procedures
- Insurers, with respect to determining liabilities for traffic code violations during ADS operations
- State and metropolitan planning organizations, in consideration of how and where traffic regulation apply across facilities those agencies manage

CHAPTER 4. FRAMEWORK REQUIREMENTS

The prototype regulations data framework has demonstrated the approach to and viability of providing regulations data to ADS developers and systems. A robust pilot deployment can specify requirements on the physical, informational, and communications components and interfaces to direct system development and provide a basis for verification testing.

FUNCTIONAL REQUIREMENTS

Functional requirements specify what functions and processes are to be provided by the framework to support its interfaces with the ADS and vehicle, communications, and the road infrastructural components. From the user needs identified in the operational concept, functions that need requirements specification include:

- Manage user access
- Create data elements
- Modify data elements
- View data elements
- Respond to requests for data

INTERFACE REQUIREMENTS

Interface requirements describe the intended interaction between the components. Interfaces needed for the ADS data regulations framework provide data from the framework, specify communications between the framework and an ADS, and inform ADS perception of infrastructure traffic controls relative to regulations applicable to the ODD. Interface requirements are needed to:

- Provide user interfaces:
    - For enabling user access to the traffic regulations data
    - For creating data elements for:
        - Jurisdictions
        - Regulatory titles
        - Units of instructions from within a regulatory title
        - Traffic situations
        - Traffic control device types
    - For relating data elements to each other
    - For viewing data elements relative to:
        - Regulatory titles and instructions by jurisdiction
        - Traffic situations relative to instructions by jurisdiction
        - Traffic control device types by jurisdiction
- Provide a traffic regulations applications programming interface
- Specify interface protocols

SECURITY REQUIREMENTS

Security requirements describe the constraints and conditions under which users and other systems may access the regulations data framework. These security requirements may describe general security attributes, pending further assessment of the ADS regulations context and governance model. Security requirements might be expected to address:

- Security needed around data element management
- Access to data as specified by operations agreements

Functional elements for security may:

- Manage access to data by user account
- Track data element creation
- Track data element modification

PERFORMANCE REQUIREMENTS

Performance requirements describe the operating expectations for the pilot framework deployment, such as data storage, processing capabilities, estimated number of data requests, and data exchange latencies. Performance requirements for a pilot deployment may be substantially different than for a full-scale deployment, especially given the range of possibilities for governance.

APPLICABLE STANDARDS

It unclear that any existing formal standards will be applicable to modeling of the traffic regulations framework, but some may become more apparent as the plan is developed. The data to be managed and provided by the framework do not readily conform to any existing ITS standards. Traffic control devices described within the framework data will conform to devices the *MUTCD* defines.

CHAPTER 5. DESIGN AND IMPLEMENTATION

This chapter describes the design and implementation of a traffic regulation data framework. The objective of the design and implementation is to fulfill the intent of the operational concept described in chapter 3 for data and interfaces to support providing traffic regulations data to ADS.

TRAFFIC REGULATIONS DATA FRAMEWORK DESIGN

The architectural intent and concepts for the regulations data framework are described in the operational concept and are implemented in the framework design. The description of the design in this chapter is based on the Proof-of-Concept Demonstration Report prepared in a prior task for this project.[49]

Challenges and Limitations of Framework Design

Implementing a traffic regulations framework for use by ADS has challenges deriving from the nature of traffic regulations created for human drivers and from the limitations of automation technologies. These challenges include:

- 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, such as "do this, then this." Future work in translation of traffic regulations for ADS applications may need to develop a semantic standard for rules and controls.
- ADS development environments and simulations do not have standard interfaces for traffic rules and controls. ADS development generally embeds interpretation of rules and controls in the code for specific ODDs.
- Traffic controls relate to specific rules within the regulations, but these relationships are not one-to-one. Rules for a right turn on a red traffic signal may be confined to a single bounded set of instructions in a traffic code. There may be multiple standard sign configurations associated with a right turn on red, each for a different setting or circumstance.

[49]FHWA, *Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information – Proof-of-Concept* Demonstration Report, FHWA-HOP-21-040 (Washington: USDOT, 2021).

- Some regulations are interpreted in driver manuals with more specific information. The regulation describes what should be done or not; the information 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 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 from vehicles, although changes will be logged and determinable from the database.

Similar rules in different jurisdictions need to be linked to the extent that they apply to identical driving situations. Consistency in labeling and attributes for driving situations would, at minimum, enable an ADS to be aware of changes in local regulations for common situations like right turn on red or U-turns. Because there is no common reference scheme for traffic regulations, 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 regulations provide 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 in which 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 so as to identify specific differences.

Traffic regulations need to be identified with the applicable traffic controls—markings and signs, as well as 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 onboard 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 information in driver manuals does not need to be included in the framework. Such information is not regulatory and may not apply to ADS. An ADS might then, however, violate human driver expectations (e.g., for following distance) if information for human drivers is not applied.

The number of jurisdictions in the United States and the variability of traffic regulations among them preclude populating the demonstration regulations framework with all those 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 investigating natural language processing and machine learning techniques.

PROTOTYPE TRAFFIC REGULATIONS DATA FRAMEWORK IMPLEMENTATION

The prototype implementation of the traffic regulations data framework is described in the Proof-of-Concept Demonstration Report[50] and summarized in this section.

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 but should protect the integrity and authority of the regulations. Although other data framework implementations could be used, a blockchain's published and distributed ledger of records lends itself well to this situation.

A blockchain peer-to-peer network enables jurisdictions to assert/attach their authority to and verify the integrity of their published traffic regulations. That 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 received regulations to verify that the 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.

User Interface

An ADS traffic regulations data framework needs interfaces for administratively capturing the regulations data and for providing data to end users and systems. A fully developed interface

[50] Ibid.

includes a user login so that the system can distinguish between administrative and end user accounts.

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 minimum of two independent reviewers would then ensure records quality. Creators would not be enabled to validate new or modified records, and validators would not be enabled to approve those records. A third administrator with appropriate authority, perhaps as a supervisor or SME, would approve new or modified records.

An administrative user adds new regulations records by selecting and entering data elements to create records for the regulations applicable to a jurisdiction:

- A "jurisdiction" data element identifies and sets boundaries for the one for which traffic regulations records are being created.
- A "title" data element describes the collective body of traffic regulations for which the records are being created and provides data entry for the appropriate source bibliographic and internet uniform resource locator (URL) references.
- An "instruction" element 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 "instruction" is linked to a list of one or more such driving "situations."
- "Traffic control types" link traffic regulations to the devices (e.g., signs, signals, and pavement markings) deployed to roadways to indicate that those controls (and the regulations behind them) are in force at particular locations. The *MUTCD*[51] or the jurisdictional equivalent as specified in its traffic regulations will define traffic control device standards.

End User Interface

The user interface enables end users to view the ADS traffic regulations data captured within the framework. For the demonstration prototype framework, users can select from a list of jurisdictions for which regulations have been captured in the data framework. When users select a jurisdiction, a list of regulatory instructions for that jurisdiction is displayed. The text of the instruction is displayed when users select a particular instruction.

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

Situations to which regulations may apply can be presented in a table that lists 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 identified in the table as "TBD" (to be determined). Users may select a particular instruction in the table to display the text of that instruction, or they may download the table in CSV format.

Users can display traffic control types associated with jurisdictions. When users select a traffic control type, an image of the associated traffic control device (for example, a stop sign) is displayed.

Prototype API

The ADS regulations data framework is accessed using three application programming interfaces (API): jurisdiction, boundaries, and situations. The interfaces are accessed through hypertext transport protocol and posting specifically named parameters to a URL endpoint. Responses are 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 from the jurisdiction interface. The response contains the geocoordinates (in decimal degrees) of a bounding box for the requested boundary, plus the list of geocoordinates that defines the region.

The situations interface URI endpoint is "api/situations," and its parameters is "id." In this case, the id is also the unique identifier for a jurisdiction determined from 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.[52]

GAPS AND NEXT STEPS

Humans write traffic regulations for human interpretation. They presume a common understanding of the roadway context, general driver-vehicle interactions, and driver intentions.

Traffic regulations are not prescriptions for driver behavior; they are constraints on behavior. As such, they are generally not procedural or algorithmic. Traffic regulations depend on the presumed understanding of the roadway, driver-vehicle interactions, and driver intent as context for interpreting those constraints. They may also require information or judgments that are

[52]GitHub, Inc. 2022. "usdot-fhwa-stol/ads-traffic regs" (web page). https://github.com/usdot-fhwa-stol/ads-traffic-regs/tree/cherneysp-initial, last accessed December 20, 2022.

implicit to human applications of the regulations but may be difficult for an ADS to interpret. For example, how would an ADS interpret a reasonable following distance or if children are present? These presumed contexts are identified in the prototype traffic regulations data framework as a set of situations that the driver might encounter. The regulations are associated with those situations to provide a logical structure for associating regulations information with jurisdictions and traffic controls.

ADS behaviors, on the other hand, are explicitly algorithmic. Data from sensors set a geophysical context in which vehicle trajectories and controls are computed to fulfill a travel intent at the lowest cost or risk. These algorithms are designed for ODDs that may be as general as traveling on a two-lane interstate highway, or as specific as a particular roadway where every sign, piece of roadway furniture, and curb is digitally mapped.

The situations described in the traffic regulations and the ODDs used in any particular ADS development program may be intended to cover the same sets of driving behaviors, but there are no explicit mappings between the two. The approach in this prototype traffic regulations data framework demonstration is to identify a set of regulatory situations from the *UVC* as a notional standardization for interpreting the rules of the road. The framework itself is a catalog of situations and regulations as particular jurisdictions have encoded them. An ADS developer can access those regulations for particular jurisdictions and situations that may be relevant to their ODDs to encode the constraints on driving behavior. Determining vehicle location relative to the jurisdictional boundaries enables the algorithms to determine which particular rules apply at that location.

This approach has significant limitations in scaling to broader sets of jurisdictions and complex situations involving multiple situations, such as stopping at a traffic signal to make a right turn within a school zone. Mapping the state space of these situations with the ODDs in which the ADS is intended to operate is itself a complex configuration management problem. At a minimum, the number of situation-ODD mappings scales geometrically with the number of jurisdictions and ODDs.

These state-mapping problems can be approached through standardization of the objects—in this case, the regulations and the ODDs—and interfaces through which the objects interact. A data dictionary and interface specification can be created to help providers (in this case, the regulators) and consumers (the ADS developers and vehicles) in the exchange of data. Neither the traffic regulations, which are longstanding and belong to their respective political jurisdictions, nor the ODDs, which are defined at the sole discretion of the ADS developers, are standardized or likely to be so in the near term. The use of driving situations in this prototype demonstration is an attempt to find some middle ground for reference.

Normalization of the regulations themselves may be unlikely, but it is possible to conceive of a set of deconstructed regulations that would share situations and interpretations to reduce the current variability across jurisdictions. This is somewhat the case already for jurisdictions that have closely followed the model of the *UVC*. It still has challenges with respect to conformance to particular traffic rules in those jurisdictions and with the potential liabilities of interpreting statutory traffic laws for the purpose of standardization.

It may also be possible to convene stakeholders to develop a standard set of ODDs to which future ADS development might conform. The development of ADS in accordance with the standard might still be at the discretion of the developers, but it would create a framework around which the interpretation of regulations might find some structure.

CHAPTER 6. VERIFICATION AND VALIDATION PLAN

This chapter describes the testing needed to verify that the pilot demonstration system meets the requirements and to validate its use and operations relative to user needs. A test plan specific to the requirements and final operational concept will be needed to structure and formalize the testing.

The verification and validation plan should follow general systems engineering practices for effective and complete testing. The test procedures should be reasonable, repeatable, and reproducible, which are defined as follows:

- Reasonable—Setting minimum performance requirements necessitates that the test burden should be reasonable, rather than subscribing to higher standards with no perceivable benefit. The range of potential scenarios is too large to test every case, so procedures describe representative needs and the minimum performance. As applied to the prototype regulations framework, simulation testing addresses two scenarios (left lane driving on freeway and right turn on red) that reasonably exercised system capabilities.

- Repeatable—The same test conducted multiple times should yield the same results. Inputs must be controllable, and conditions must be reasonable. This is key when a failure is observed, especially if that test failure can be repeated.

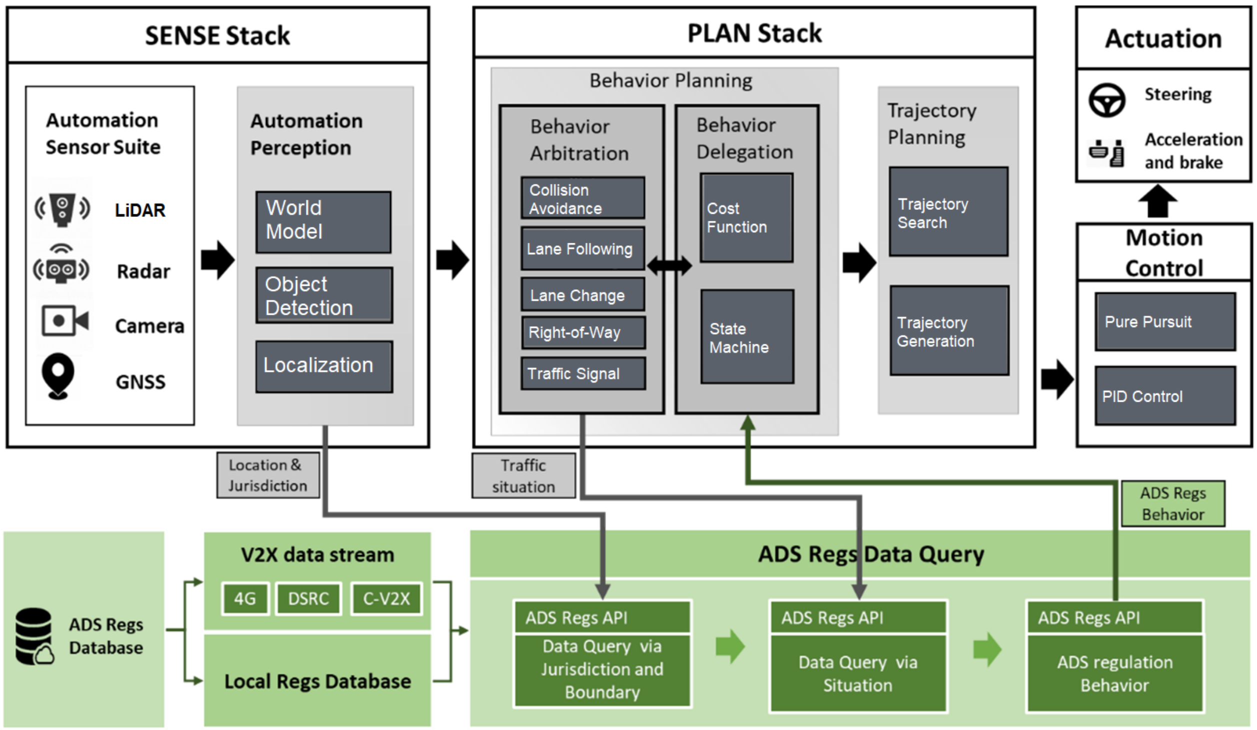
- Reproducible—The test must be described in enough detail that it can be performed at another location and get the same result. The system is intended to apply to jurisdictions throughout the United States, so the tests must be reproducible nationwide (whether physically or in simulation).

FUNCTIONAL VERIFICATION

The functional verification concerns the general assessment and demonstration to verify that the traffic regulations data framework meets its specified functional, interface, security, and performance requirements. This section focuses on testing software components of the regulation data framework.

The objective of testing is to show how traffic laws and regulations, as stored in the traffic regulations framework, can be processed by a typical ADS platform and subsequently affect the operational behavior of ADS-equipped vehicles. The functional verification needs to verify that the new components developed in the framework meet the functional requirements. These new components include a traffic laws and regulations database, APIs for the data request, and APIs for ADS software to comprehend regulations information from the database.

The upper part of figure 8 shows a standard ADS software platform, including four stacks (i.e., sense, plan, control, and actuation). The ADS regulations database can be local on the vehicle storage (downloaded before the trip) or accessed in realtime 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. Queries from the database are based on vehicle jurisdictions and boundaries and the driving situation the vehicle is in and generate allowed ADS regulation-related behavior. This behavior output will be fed to the behavior planning module of the plan stack, and this information is integrated into the overall behavior planning software module, meaning that the generated ADS behavior will be constrained by the relevant ADS regulations.



Source: Federal Highway Administration.

API = application programming interface; DSRC = dedicated short-range communication; GNSS = global navigation satellite systems; LiDAR = light detection and ranging; PID = proportional-integral-derivative; radar = radio detection and ranging; V2X = vehicle-to-everything.

Figure 8. Illustration. Automated driving systems (ADS) platform architecture with traffic regulations database.

As shown in figure 8, the added components of the regulation data framework are software-based (i.e., database and APIs); therefore, automated driving simulators can be relied on to verify the functions of each software component. Automated driving simulators offer the potential benefit of testing perception and control algorithms embedded in real software because they support simulation of different vehicles with accurate vehicle dynamics, sensor suites, environmental conditions, control of all static and dynamic actors, control software, and map generation that enable AV simulations. These capabilities enable more detailed testing of traffic regulations framework software directly in the simulation environment under different key scenarios. Using an automated driving simulator for functional verification was demonstrated for the proof-of-concept traffic regulations data framework with CARLA,[53,54] an open-source simulation software system specifically designed for ADS.

With this approach, the functional verification will report the actual performance of each software component in the traffic regulation software system. The performance metrics for the functional verification are yet to be developed. The functional requirements for the regulation database should concern aspects such as response time, required data structure, and security. The functional requirements for the APIs should include aspects such as regulation comprehension accuracy and capability to translate regulation information to the format that can be integrated with existing ADS platform software.

NEEDS VALIDATION

The needs validation consists of a general assessment and demonstration that the traffic regulations data framework meets the stakeholder needs identified for the test environments and use cases.

Simulation and field testing can be applied for needs validation. The simulation testing methods are similar to what is described in verification. Through an automated driving simulator, the predefined needs described in the operational concept for the traffic regulations database and APIs can be validated at a low cost. This can be built on the functional verification effort, which focuses on each component of the system. The simulation testing, however, cannot completely fulfill the testing requirements because the resultant ADS-equipped vehicle behavior in response to regulations is also dependent on the vehicle hardware platforms and real-world traffic and infrastructure environment. Therefore, field testing on a closed test track or selected open public road with different levels of live traffic should also be used for better needs validation.

The purpose of testing is to collect vehicle behavior performance metrics and validate if the software (traffic regulations database and APIs) meets the needs. On the test track, it is possible to conduct testing under controlled environments, where various vehicle operations and infrastructure scenarios can be replicated to some extent for testing purposes. The field testing could also be conducted on public roads with live traffic. Although the on-road testing is limited in the number of scenarios to be tested, one key difference is the existence of live traffic, which will dynamically interact with all other real vehicles on the road, and this offers higher levels of reality for testing in terms of driving environments, interactions with other traffic, and match between regulations with real-world infrastructure.

Data collected from track and public road testing can be used not only to evaluate vehicle behavior performance metrics but also to identify further needs for system enhancements. The data can capture the response of existing ADS vehicles to different types of regulations and be used to better calibrate the automated driving simulation for both verification and validation purposes.

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[53] *FHWA, Automated Driving Systems (ADS) Operational Behavior and Traffic Regulations Information – Proof-of-Concept Demonstration Report,* FHWA-HOP-21-040 (Washington: USDOT, 2021).

[54] CARLA. 2022. Cars Learning to Act (software). Version 0.910. https://carla.org/, last accessed December 20, 2022.

Similarly, key performance metrics to validate the needs of the system (i.e., to measure the overall system behavior) should be developed during this step. The performance metrics should concern the resultant ADS behavior after the ADS system processes the information from traffic regulation databases via the APIs. Generally, the performance metrics should cover, at minimum, the expected response to corresponding regulations and safe vehicle operations.

The validation needs to ensure that ADS vehicles can query corresponding regulation information and behave in an expected manner after receiving and processing the regulation information. For example, if right turn on red is not allowed at certain intersections, any ADS vehicle needs to be able to access this information, stored onboard or via wireless communication, and smoothly stop at the stop bar to wait for the next green before the ADS vehicle turns right. Therefore, this metric should be regulation-dependent and defined separately for validation regulations of different categories in the database.

Safe vehicle operation is the basic requirement for any ADS vehicle operation on the road. Standard performance metrics can be used as long as they capture the possible response to regulation information. For example, regulations that require a vehicle to come to a stop at certain locations need to ensure the vehicle's trajectory toward that stop are smooth and will not generate safety hazards for the following vehicles. To measure safe vehicle operations, performance metrics such as separation distances, accelerations, speed oscillations, travel speeds (as compared to the safe travel speed), and time-to-collision can be used.

GAPS AND NEXT STEPS

During this project, an initial POC demonstration was performed using automated driving simulation for two selected scenarios. While the demonstration was successful, the verification and validation processes were informal. The functional verification and needs validation testing discussed in this chapter recommend generalized approaches for testing traffic regulations database framework software. Further enhancements to the testing methods and procedure are needed.

From the testing perspective, additional efforts are needed to develop more comprehensive simulation and field-testing functionalities. For instance, the ADS software platform, from perception to control, should be modeled alongside the ADS vehicle hardware platform. To meet this expectation, various testing approaches combining real-world and virtual simulation tests can be developed and adopted. Integrated testing strategies that use both real-world and virtual testing are key to leveraging their testing methodology benefits while minimizing their downsides. Simulation allows for checking the behavior of AVs in a huge number of scenarios, environments, system configurations, and driver characteristics, but physical field testing is still the gold standard to verify virtual test results. This verification increases confidence in virtual results for cases that cannot be tested due to economic or safety reasons.

One solution to this problem is a combination of physical and virtual testing, executed at the component, subsystem, and system level. The virtual simulation testing is usually carried out in several steps by applying everything-in-the-loop (XIL) verification and validation. XIL testing is a multistage testing process that allows for component or software requirements verification and validation at any development stage. The first step is usually a model-in-the-loop approach, which enables testing without dedicated hardware. This level of development typically involves high-level abstraction of the software frameworks running on general purpose computers. The next step is usually a software-in-the-loop (SIL) validation, where the actual implementation of the developed model is evaluated on general purpose hardware. The final step of XIL testing, prior to vehicle testing, is hardware-in-the-loop (HIL), which involves the final hardware, running the final software, with inputs and outputs connected to a simulator. Modern vehicles integrate so many components that the integration phase has become increasingly complex, requiring a multistep verification process. The final step of the verification and validation stage is to perform integration testing on-road (closed-course or public deployments), which requires a full vehicle prototype to integrate the developed system. This systematic approach provides greater confidence in deploying safer algorithms on vehicles, and the verification and validation testing should follow these technical concepts, dependent on the testing needs.

Starting from SIL and HIL, full working prototypes are needed. For this project, only a limited demonstration of traffic regulations of certain categories is included in the database. A full working prototype will be needed in future phases of this effort. One recommendation is to work with one or multiple selected IOOs and develop database prototypes specific to their locations such that the database will include not only general laws and regulations from the *UVC* but also local traffic rules and regulations. This will enable testing and demonstration of the traffic regulations framework under a more complete set of scenarios.

U.S. Department of Transportation
Federal Highway Administration Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590
https://ops.fhwa.dot.gov

April 2024

FHWA-HOP-21-039