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

Concept of Use

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16. Abstract

This research investigates the challenges of establishing an automated driving system (ADS)-ready traffic laws and the regulations database, as well as proposed access and exchange requirements to support sharing and consumption of the information within the ADS ecosystem. It also describes basic requirements for collaboration among State and local traffic code stakeholders, as well as ADS behavior subject matter experts. This report looks at currently available data that support automated vehicle integration into our roadway system, and investigates the issue of inconsistencies in basic traffic laws across the nation and how they affect ADS behavior. This concept of use describes the background, stakeholder needs, design concepts, use cases, and other considerations for the design and development of an ADS regulations data framework.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

AAA	American Automobile Association
AAMVA	American Association of Motor Vehicle Administrators
AASHTO	American Association of State Highway Officials
ADAS	advanced driver assistance system
ADS	automated driving system
API	application programming interface
ARTBA	American Road & Transportation Builders Association
AV	automated vehicle
CADS	cooperative automated driving system
CAT	Cooperative Automated Transportation
CDA	cooperative driving automation
COU	concept of use
CSV	comma-separated values
DAVI	Data for AV Integration
DOT	department of transportation
EPS	Encapsulated PostScript
FHWA	Federal Highway Administration
FIPS	Federal Information Processing Standards
FMVSS	Federal Motor Vehicle Safety Standards
Gbit/s	gigabit per second
HTML	Hypertext Markup Language
I2V	infrastructure-to-vehicle
IOO	infrastructure owner-operator
ITS	intelligent transportation systems
ITS–JPO	Intelligent Transportation System Joint Program Office
JSON	JavaScript Object Notation

Kbits	kilobit
LiDAR	light detection and ranging
MAP–21	Moving Ahead for Progress in the 21st Century Act
MUTCD	Manual on Uniform Traffic Control Devices
NCSL	National Council of State Legislatures
NDAA	National District Attorneys Association
NHTSA	National Highway Traffic Safety Administration
O&M	ownership and maintenance
ODD	operational design domain
OEM	original equipment manufacturer
OSADP	Open Source Application Development Portal
PDF	portable document format
RGB	red-green-blue
ROS	Robot Operating System™
SAE	Society of Automotive Engineers
SHP	shape file
SME	subject matter expert
SPaT	Signal Phase and Timing
TSMO	transportation system management and operations
USDOT	U.S. Department of Transportation
UVC	Uniform Vehicle Code
V2I	vehicle-to-infrastructure
WZAD	work zone activity data
WZDI	Work Zone Data Initiative
WZDx	Work Zone Data Exchange
XML	eXtensible Markup Language
ZIP	Zone Improvement Plan

CHAPTER 1. INTRODUCTION

BACKGROUND

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

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

Among the key aspects of ADS planning, deployment, and operations, access to data is a critical enabler of safe, efficient, and accessible integration of AVs into the transportation system. On 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 and marked the beginning of a new phase of dialogue with public and private-sector stakeholders to accelerate safe deployment of AVs.

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

- Monitoring planned and unplanned work zones.

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

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

- 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 will facilitate the development of ADS behavior and roadway adaptations that fulfill the vision of safe and effective ADS operations. Having consistent and accurate information about jurisdictional traffic regulations relates to ADS compliance that will support safe operations and performance on public roadways. The ADS Operational Behavior and Traffic Regulation Database framework is, therefore, a key requirement for realizing effective, robust digital transportation systems for AV integration. It consists of a comprehensive, structured database of traffic regulations that developers could use to set basic programming standards regarding traffic regulations.

There are challenges to developing ADS to account 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 among jurisdictions across the country in format, structure, and implementation. Without common data exchanges, it is almost impossible to develop ADS software that can ensure optimal ADS performance under varying sets of traffic regulations. In short, ADS developers have indicated a need for a traffic regulation database that supports consistent indication of traffic regulation. This traffic regulation database will assist in the development testing, and later operation of ADS that is compliant with jurisdictional traffic laws resulting in safe ADS operational behavior.

PURPOSE

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

For consistency and interoperability, and to support other databases of existing traffic regulations and their interaction with ADS, it is necessary to develop a comprehensive database framework to support the incorporation of all traffic regulations that enable ADS behavior development and operation. The ultimate goal is to facilitate a traffic regulation specification that supports development and subsequent operations of traffic with ADS-equipped vehicles. This project involves detailed 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 regulation database framework, conduct of a simulated proof-of-concept laboratory testbed-simulated demonstration, and development of a model testing plan for a future collaborative implementation of AV integration with the traffic laws and regulations database framework.

The purpose of this COU is to describe an approach to establishing a traffic regulations data framework in support of ADS development. It first lays out the background and context for traffic regulations information relative to AVs and highway automation. The COU then describes the need for the framework from the perspectives of legislative, administrative, traffic control, IOO, vehicle operator, enforcement, and ADS developer stakeholders. The proposed framework concepts are described in terms of the data elements to be captured therein, a logical structure, formats, and interfaces. Use cases are used to describe the applications and interactions of stakeholders with the proposed framework, including its relationship to potential operational design domains (ODD) for the ADS-equipped vehicles. The COU concludes with a discussion of other considerations in the development and use of a regulations framework, such as testing, operations and maintenance, security, and privacy.

The organization of the COU is as follows:

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

Chapter 2 describes the context of traffic regulation, AVs, and highway automation.

Chapter 3 describes the needs for traffic regulation data in ADS development from the perspectives of the stakeholders in the regulations data life cycle.

Chapter 4 describes concepts for a regulations data framework.

Chapter 5 identifies and describes use cases for a regulations data framework.

Chapter 6 investigates implications of other factors in a system development and deployment for a regulations data framework.

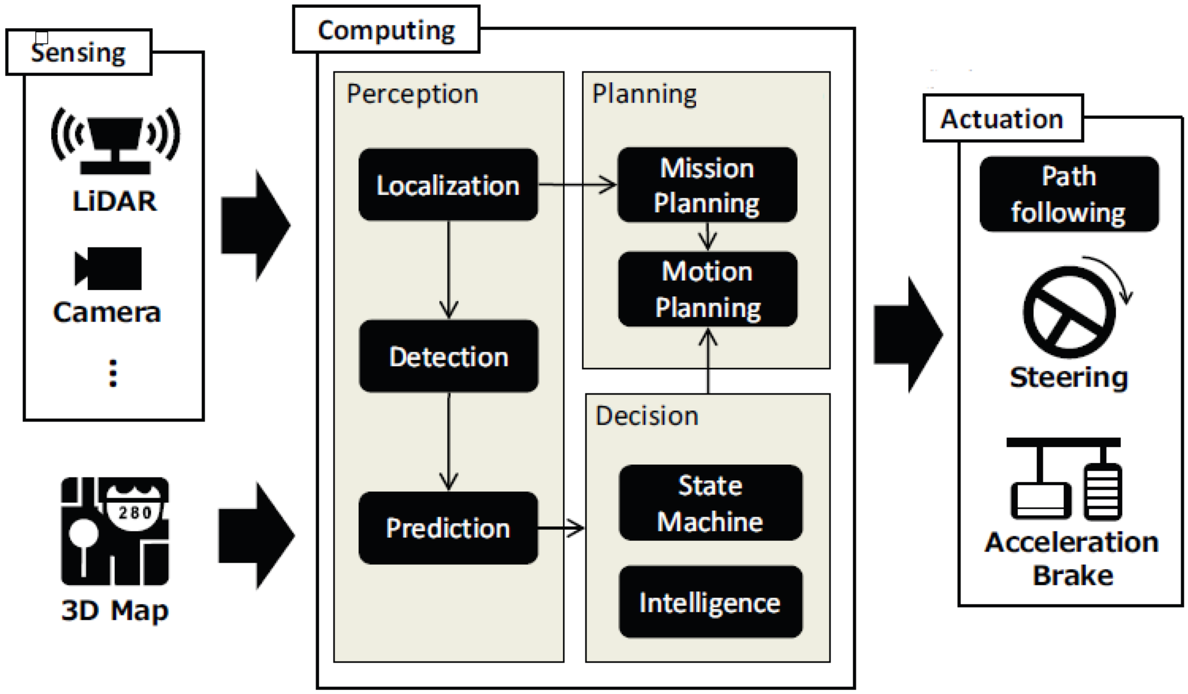
CHAPTER 2. TRAFFIC REGULATIONS, AUTOMATED VEHICLES, AND HIGHWAY AUTOMATION

This chapter introduces national highway automation and automated driving systems (ADS) technologies and behavior.

AUTOMATED DRIVING SYSTEMS AND OPERATIONAL BEHAVIORS

As cyber-physical systems, ADS-equipped vehicles can be abstracted into sensing, computing, and actuation modules, as shown in figure 1. Sensing devices, such as laser scanners (light detection and ranging [LiDAR]) 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 generate the control commands. Computation is a major component of self-driving technology. Scene recognition, for instance, requires 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. Combined, the modules are exemplified by the well-known open-source automated driving software, Autoware™. Figure 1 shows the basic control and data flow for an autonomous vehicle. Sensors record environmental information that serves as input data for the artificial intelligence core, which includes data fusion for vehicle localization based on filtering techniques, machine learning methods for predicting other vehicle's behavior, and intelligent decision-making in mission/motion planning using optimal control or reinforcement learning approaches. Three-dimensional maps are becoming commonplace for self-driving systems, particularly in urban areas, as a complement to 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.

Another important concept related to ADS operational behavior is the operation design domain (ODD). In SAE's definitions of automation levels, a driving mode is a type of driving scenario with specific dynamic driving task requirements (e.g., expressway merging, high-speed cruising, low-speed traffic jam, and closed-campus operations). In SAE's levels of driving automation, shown in figure 2, 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 dynamic driving task 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.



Source: Autoware.

Figure 1. Diagram. Automated driving vehicle platform (Autoware).[3]

[3] "Wiki Autoware Foundation/Autoware.AI/Autoware," GitLab, accessed May 11, 2020, https://gitlab.com/autowarefoundation/autoware.ai/autoware/-/wikis/home.

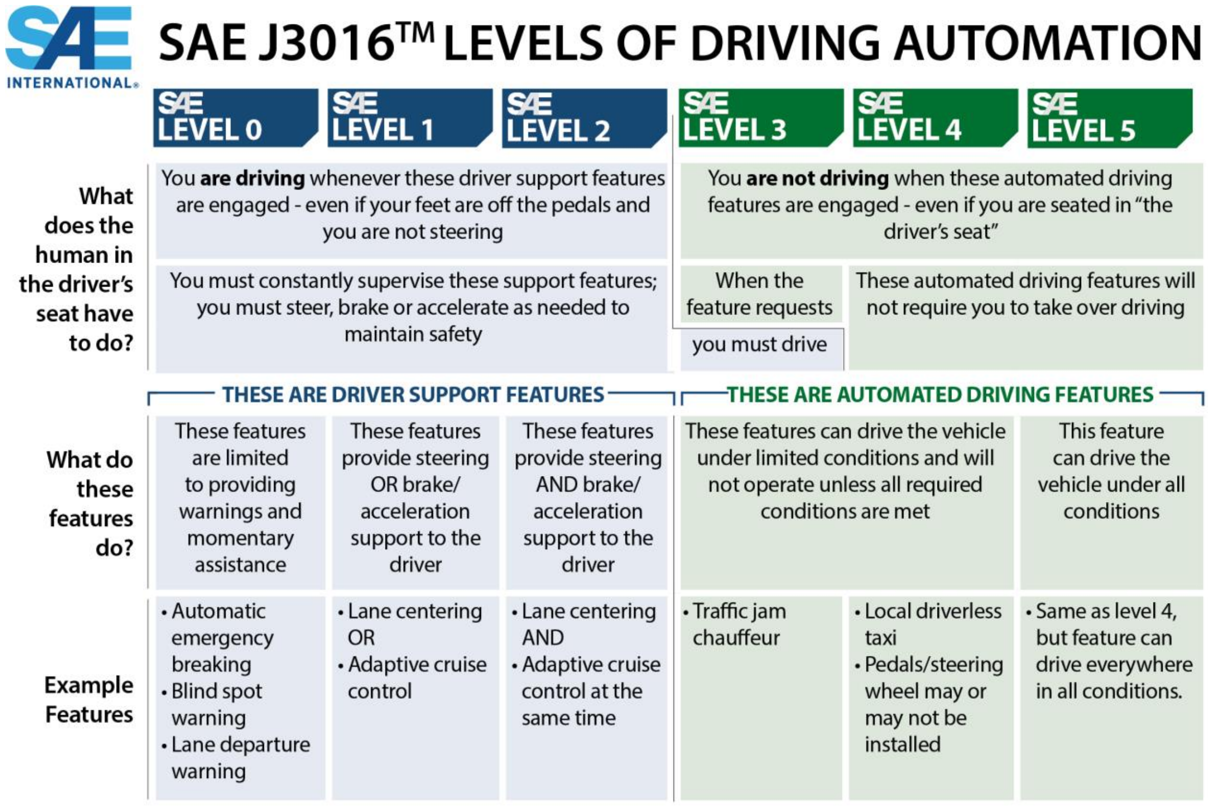


Figure 2. Illustration. SAE International® definition of levels of automation.

Based on the understanding of ADS software structure, any ADS component under different rules and regulations can affect ADS operational behavior. For example, yellow signal legends and timing may vary along and among urban corridors, such that when an AV detects a yellow light, 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 use of the left-most 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 regular driving lane), this traffic rule will potentially result in frequent lane-change behavior on freeways, causing inefficient traffic operations, demonstrating that different traffic laws and regulations may result in dramatically different ADS behaviors, even with the same ADS software. It is critical to provide ADS vehicles with accurate traffic regulation information and to

[4] "SAE International Releases Updated Visual Chart for Its 'Levels of Driving Automation' Standard for Self-Driving Vehicles," SAE International®, December 12, 2018, https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles.

design ADS software to explicitly incorporate the regulations to ensure safe and efficient behavior.

Additionally, ADS only involves single-vehicle automation through onboard sensing and computing. However, SAE is working on a new standard, SAE J3216_202005™,[5] to define cooperative driving automation (CDA), which enables and supports ADS automation through machine-to-machine communications. In fact, CDA becomes even more relevant when traffic regulation databases are shared with AVs enabled with CDA to communicate this information. The Federal Highway Administration's (FHWA) CARMA℠ research platform is designed using open-source software to test CDA concepts to improve transportation system management and operations (TSMO) using CARMA Cloud℠, a cloud-based framework. Information from databases of traffic regulations can be shared with ADS vehicles enabled with CDA through the cloud or other vehicle-to-infrastructure (V2I) communication.

EMERGING AUTOMATED VEHICLE DATA FRAMEWORKS

The U.S. Department of Transportation (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 introduction of two most recent frameworks related to ADS.

Data for Automated Vehicle Integration

USDOT launched Data for Automated Vehicle Integration[6] (DAVI), shown in Figure 3, as an initiative to identify, prioritize, monitor, and address data exchange needs for AV integration across the modes of transportation. Access to data is a critical enabler of safe, efficient, and accessible integration of AVs into the transportation system. Lack of access to data could impede AV integration and delay safe introduction.

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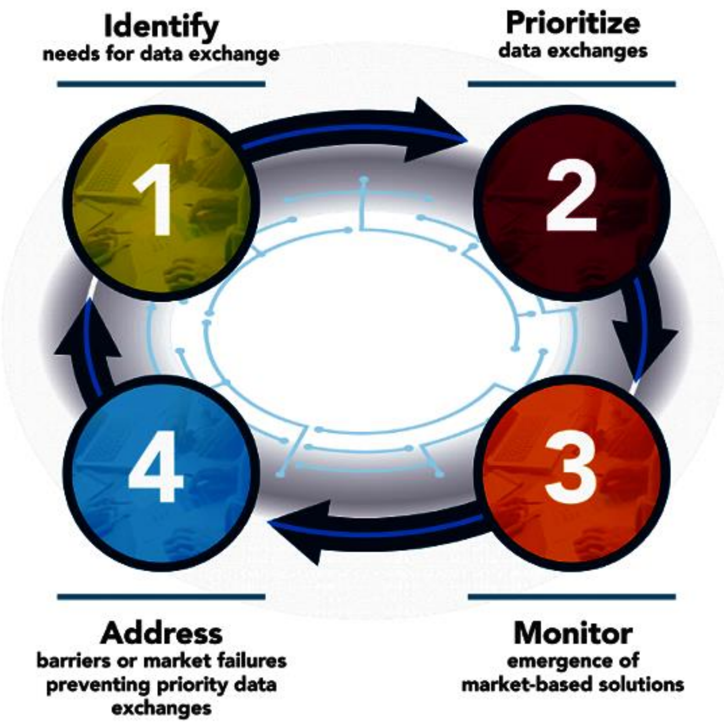
[5] https://www.sae.org/standards/content/j3216_202005/.

[6] "Data for Automated Vehicle Integration (DAVI)," USDOT, last updated Wednesday, May 20, 2020, https://www.transportation.gov/av/data.



Source: USDOT.

Figure 3. Illustration. Framework of Data for Automated Vehicle Integration.[7]

The USDOT DAVI framework provides a common language for identifying and prioritizing data exchange needs across traditional silos. It is designed to help 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 continues to refine and update the framework based on stakeholder inputs.

In December 2017, USDOT hosted the Roundtable on Data for Automated Vehicle Safety to discuss potential priorities for voluntary data exchanges to accelerate safe AV integration. The department kicked off the Work Zone Data Exchange[8] (WZDx) project in March 2018 to take on one of the priorities identified at the roundtable. The summary notes also call for enhanced inventories for roadways, which include high-definition maps already being developed. Developing inventories of fixed objects on the road, such as traffic signs, is not a difficult task and it has been done for many locations by private sectors. The rules behind the infrastructure

[7] "Data for Automated Vehicle Integration (DAVI)," USDOT, last updated Wednesday, May 20, 2020, https://www.transportation.gov/av/data.

[8] "Work Zone Data Exchange (WZDx)," USDOT, last updated Tuesday, June 30, 2020, https://www.transportation.gov/av/data/wzdx.

(i.e., traffic laws and regulations) also need to be part of the map. Unfortunately, no complete digital database exists that addresses this key issue.

Work Zone Data Exchange and Initiative

Up-to-date information about dynamic road conditions, such as construction events, can help ADS and humans navigate safely and efficiently. Many infrastructure owner-operators (IOO) maintain data on work zone activity. However, a lack of common data standards and convening mechanisms makes it difficult and costly for third parties—including original equipment manufacturers (OEM) and navigation applications—to access and use these data across various jurisdictions.

The purpose of FHWA's Work Zone Data Initiative (WZDI) is to develop a model practice for managing work zone activity data (WZAD) and to create a consistent language, through the development of a data dictionary and supporting implementation documents, for communicating work zone activity information across jurisdictional and organizational boundaries. The effort promotes a stakeholder- and 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 one of the key use categories.

Implementation of this language is occurring through the USDOT Intelligent Transportation System Joint Program Office's (ITS–JPO) WZDx. The WZDx is a publicly available basic work zone data specification[9] intended to jump-start voluntary adoption of a common data language by data producers and users across the country. By using WZDI guidance to determine agency-specific needs and uses for work zone data, and subsequently developing a customized specification using the WZDx as a foundation, 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.

The WZDx working group is working to describe a set of common core data concepts, meanings, and enumerations to standardize a data feed specification to be used to publish work zone information. Common core is defined in this context as data elements needed for most (if not all) work zone data use cases that could possibly be defined. The data specification includes data elements that data producers (i.e., State transportation agencies and other IOOs) are already producing (required) as well as those not currently produced (optional). This common core is also considered extensible, meaning both required and optional data elements can be added to support specific use cases now and in the future.

[9] "Work Zone Data Exchange (WZDx) Specification," GitHub, last updated January 14, 2020, https://github.com/usdot-jpo-ode/jpo-wzdx/blob/master/README.md.

The WZDx data feed will be incrementally enhanced to evolve into a data feed that supports advanced warnings to AVs in and around work zones. The current version (WZDx v1.1) is a first step in this effort and highlights common core elements that serve as a foundation for required data for effective data exchange This version addresses data currently supported by existing data feeds published by public and private-sector organizations.

WZDx data producers will use the specification to make their active work zone data feeds available to non-government users. These users may then use the harmonized data in a meaningful way, which will result in establishing the voluntary data exchange of work zone data. This approach is intended to be repeatable, leading to accelerated harmonization of local data.

OVERVIEW OF TRAFFIC LAWS AND REGULATIONS

For constitutional and historical reasons, traffic regulations in the United States are enacted and administered by the States rather than the Federal government. The first statewide traffic regulations were enacted in Connecticut in 1901,[10] before automobiles were common on roadways. Other States enacted their own regulations as need and custom dictated. The first version of the Uniform Vehicle Code (UVC) appeared in 1926.[11] The first Manual on Uniform Traffic Control Devices (MUTCD) was compiled by the American Association of State Highway Officials (AASHTO) in 1935.[12] In 1966, USDOT was established.

Although not directly responsible for traffic regulation, USDOT nonetheless oversees the safety of the nation's roadways. As described in the 2013 Moving Ahead for Progress in the 21st Century Act (MAP–21),[13] the Secretary of USDOT, under Chapter 4 of Title 23 of the United States Code , "Is 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."[14] This authority is then 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[15] represents a working consensus, though it has no formal standing as a body of law and has not been updated since 2000. As a starting point for this analysis, however, the UVC provides a common reference for the definition of terms used in framing traffic regulations and the user categories to which the

[10] 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.

[11] J. Allen Davis, *The California Vehicle Code and the Uniform Vehicle Code*, 14 Hastings L.J. 377 (1963), https://repository.uchastings.edu/hastings_law_journal/vol14/iss4/3.

[12] "The Evolution of MUTCD," Manual on Uniform Traffic Control Devices (MUTCD), FHWA, accessed May 11, 2020, https://mutcd.fhwa.dot.gov/kno-history.htm.

[13] Moving Ahead for Progress in the 21st Century Act, Pub. L. No. 91-190 (July 6, 2012).

[14] 23 U.S.C. § 401.

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

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 of the regulations. Similarly, the UVC and State traffic codes generally point to the MUTCD, or the State's version, for the definition of particular traffic controls with which to be 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. In the broadest sense, however, AVs blur the distinction between driver and vehicle, since driving automation systems reside in the vehicle and depend on its sensors. Recent regulation of AVs views AVs as a hybrid of vehicles and drivers, and is largely limited to their licensure for ODDs in particular jurisdictions under the presumption that existing regulations on driver behavior will remain applicable.

EXISTING TRAFFIC LAWS AND TRAFFIC REGULATION DATABASES

The body of traffic laws across the United States varies from State to State and among local jurisdictions within those States. Reviewing existing traffic laws and traffic regulation databases, therefore, requires consideration of Compilation, State, and local perspectives.

Compilation Perspective

Since 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 country. Particular perspectives and use cases for the resulting traffic regulation compilation or database have driven each effort.

Justia provides a seemingly complete compilation of laws, codes, and statutes at the Federal and State levels, implicitly including traffic regulations. It appears to have been built as a portal for linking individual legal research to legal counsel. It does not address local government codes. It is primarily a set of links to documents in portable document format (PDF) and Hypertext Markup Language (HTML) format. For example: https://law.justia.com/codes/kansas/2018/chapter-8/article-15/.[16]

The American Automobile Association (AAA) *Digest of Motor Laws*[17] provides summaries of traffic laws within individual States and across the country. It categorizes traffic laws, largely along the outline of the UVC, to list summaries of relevant laws across the nation. It also provides the same summaries for all categories within a particular State. It is not a complete representation of the traffic codes and does not link to the text of the actual statutes and codes. It does not address local variability within States. https://drivinglaws.aaa.com/.[18]

The National Council of State Legislatures (NCSL) maintains a database of current legislation relating to traffic safety. It provides a view of the delineation of existing laws, the impacts of

[16] "2018 Kansas Statutes :: Chapter 8 AUTOMOBILES AND OTHER VEHICLES :: Article 15 UNIFORM ACT REGULATING TRAFFIC; RULES OF THE ROAD," Justia Law, accessed May 12, 2020, https://law.justia.com/codes/kansas/2018/chapter-8/article-15/.

[17] "AAA Digest of Motor Laws," accessed May 12, 2020, https://drivinglaws.aaa.com/.

[18] "AAA Digest of Motor Laws," https://drivinglaws.aaa.com/.

emerging technologies, and changes in public policy. It links to, but does not directly provide, the underlying and enacted bodies of traffic regulations.

> http://www.ncsl.org/research/transportation/state-traffic-safety-legislation-database.aspx#keywords.[19]

> http://www.ncsl.org/aboutus/ncslservice/state-legislative-websites-directory.aspx.[20]

NCSL also provides a database of legislation directly related to AVs.

> http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx.[21]

The National District Attorneys Association (NDAA) maintains a National Traffic Laws Center to provide support to district attorneys in enforcement of traffic law. It does not specifically provide a database of laws.

> https://ndaa.org/programs/ntlc/.[22]

The FindLaw website operated by Thomson Reuters 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. It does not specifically provide a database of laws.

> https://traffic.findlaw.com/traffic-tickets/state-traffic-laws.html.[23]

The American Road and Transportation Builders Association (ARTBA) maintains a National Work Zone Safety Information Clearinghouse[24] of links to work zone safety laws across States and territories. In many cases the website provides direct links to State laws, but notes in a disclaimer at the bottom of the web page that links are for information only and does not necessarily include all relevant statutes.

> https://www.workzonesafety.org/data-resources/laws-regulations-and-standards/state-work-zone-laws/.[25]

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[19] Ann Kitch and Gretchenn DuBois, Traffic Safety State Bill Tracking, accessed May 12, 2020, http://www.ncsl.org/research/transportation/state-traffic-safety-legislation-database.aspx.

[20] Administration, State Legislative Websites Directory, accessed May 12, 2020, https://www.ncsl.org/aboutus/ncslservice/state-legislative-websites-directory.aspx.

[21] Douglas Shinkle and Gretchenn Dubois, "Autonomous Vehicles: Self-Driving Vehicles Enacted Legislation," Autonomous Vehicles|Self-Driving Vehicles Enacted Legislation, accessed May 12, 2020, http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx.

[22] "National Traffic Law Center," National District Attorneys Association, January 30, 2020, https://ndaa.org/programs/ntlc/.

[23] "State Traffic Laws," Findlaw, accessed May 12, 2020, https://traffic.findlaw.com/traffic-tickets/state-traffic-laws.html.

[24] "State Work Zone Laws," The National Work Zone Safety Information Clearinghouse, October 25, 2019, https://www.workzonesafety.org/data-resources/laws-regulations-and-standards/state-work-zone-laws/.

[25] "State Work Zone Laws," https://www.workzonesafety.org/data-resources/laws-regulations-and-standards/state-work-zone-laws/.

State Perspectives

State vehicle and traffic regulations are, in all cases, 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 the 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 PDFs of 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*.[26]

The MUTCD provides another layer of consistency in traffic control deployments that complements the influence of the UVC. The State traffic codes prescribe that the State must have a standard for uniform traffic control and that drivers must obey the instructions of any official traffic control device. FHWA maintains an informational web page on the status of the States' traffic control device specifications at https://mutcd.fhwa.dot.gov/resources/state_info/index.htm.[27]

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.[28] However, no national databases of traffic control 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, townships, or other such entities as identified in the respective States. The number and diversity of such 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. Where allowed, local regulations may modify or take exception to the State traffic regulations. The City of Overland Park, Kansas, for example, provides its municipal code online at http://online.encodeplus.com/regs/overlandpark-ks/index.aspx.[29] The code is searchable by

[26] FHWA, Detailed Analysis of ADS-Deployment Readiness of the Existing Traffic Laws and Regulations, FHWA-HOP-20-013 (Washington, DC: February 5, 2020).

[27] "MUTCDs & Traffic Control Devices Information by State," Manual on Uniform Traffic Control Devices (MUTCD), accessed May 12, 2020, https://mutcd.fhwa.dot.gov/resources/state_info/index.htm.

[28] https://www.transportation.ohio.gov/wps/portal/gov/odot/programs/traffic-regulations/traffic-regulations, accessed December 31, 2019.

[29] "Municipal Code" Overland Park, Kansas, accessed May 12, 2020, http://online.encodeplus.com/regs/overlandpark-ks/index.aspx.

keyword or browsable by section. Title 12 of that code contains traffic regulations. Exceptions to the State code would generally be described as such. For example, Section 12.04.011 states, "All traffic control devices shall conform to the manual and specifications as adopted by the State department of transportation *with the exception of handicapped parking signs* as defined in 12.04.087"[30] [italics added for emphasis]. Extensions to the referenced State regulations may not be noted as such. For example, in its traffic control signal legend, Overland Park includes a flashing yellow arrow indication, even though such an indication is not part of the code for the State of Kansas.

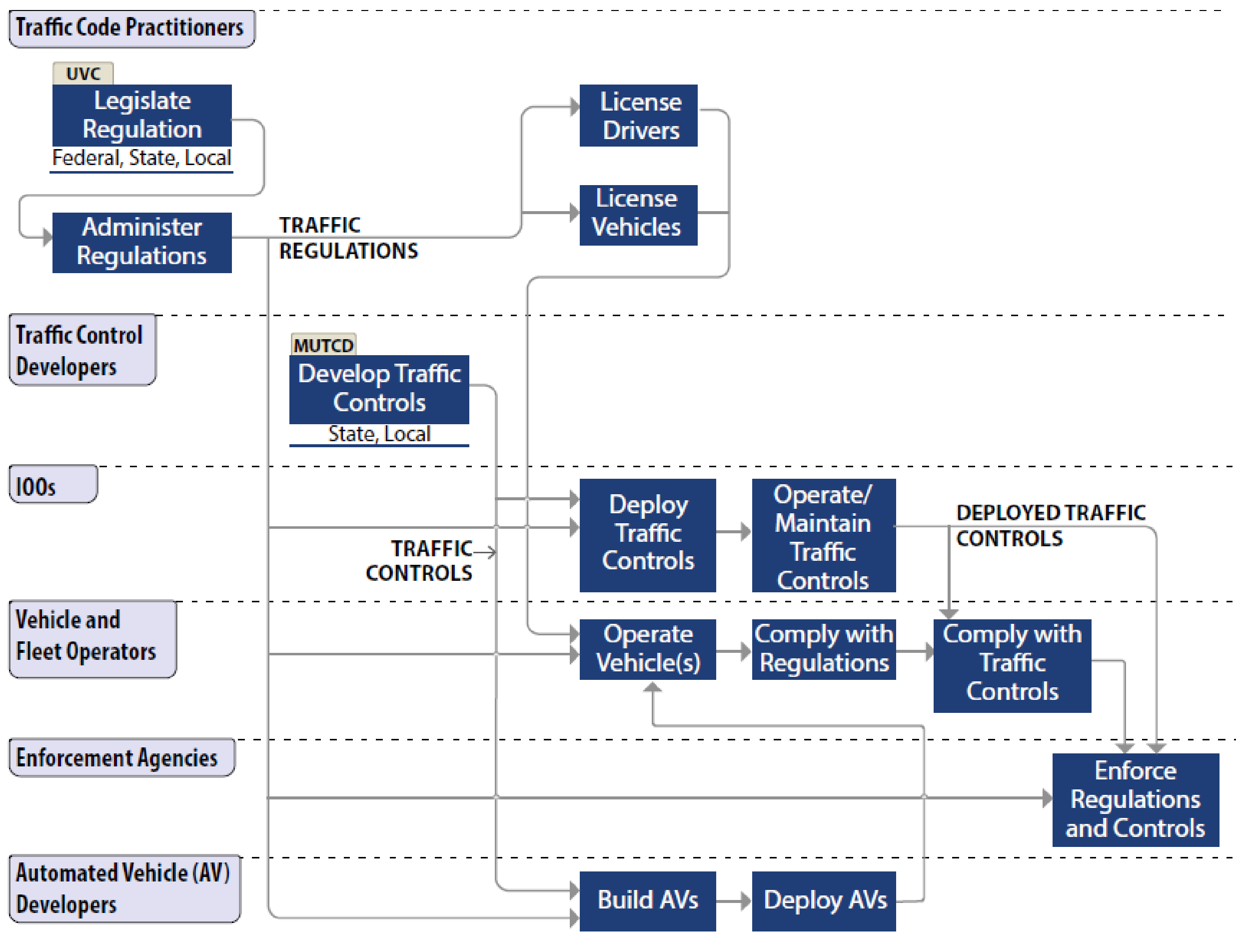
[30] Overland Park Municipal Code, Title 12, Article IV, Section 011, accessed May 12, 2020, http://online.encodeplus.com/regs/overlandpark-ks/doc-viewer.aspx#secid-3069.

CHAPTER 3. NEEDS FOR TRAFFIC REGULATION DATA IN AUTOMATED DRIVING SYSTEM DEVELOPMENT

THE NEED FOR AN AUTOMATED DRIVING SYSTEM REGULATIONS DATA FRAMEWORK

Developers of automated driving systems (ADS) and associated technologies want and will eventually need their products to work seamlessly across the nation. The deployment of automated vehicles (AV) will of course not happen everywhere at the same time, and the evolution of AVs over time will achieve higher levels of automation across more operational design domains (ODD). 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.

As seen in the prior discussion of existing traffic regulations, there is a significant diversity of traffic regulations, controls, custom, and enforcement across the nation. The essentials of the driving tasks and maneuvers are necessarily consistent, but the constraints on particular movements may vary. The basis for this variation has to do with the ways that traffic regulations are created, administered, applied in design, applied in practice, and enforced in different jurisdictions. Figure 4 depicts this process conceptually, in terms of traffic regulations, stakeholders, their actions on and use of regulations, and the flow of regulation information among activities.



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

Source: FHWA.

Figure 4. Diagram. Traffic regulation and automated vehicle 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 developers are those who develop uniform traffic control device descriptions. These developers typically are civil engineers, planners, and human factors specialists with knowledge of traffic management strategies and techniques and driver and vehicle behaviors.

- Infrastructure owner-operators (IOO) are responsible for deploying, operating, and maintaining traffic controls 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 include adjudication of the 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 broadly speaking 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 blue boxes in Figure 4 represent activities undertaken by the traffic regulation stakeholders to assure that vehicles and their drivers operate safely and effectively on the nation's roadways.

Traffic regulations are created and enacted at the Federal,[31] State, and local government levels by legislators and their staff with input from transportation agencies, and to some extent, private commercial entities and the public.

Once enacted, the regulations are administered by other State and local agencies, such as departments of transportation, departments of motor vehicles, driver license bureaus, and State highway patrol and police. These administrative groups will also license drivers and vehicles for those jurisdictions in which they will be operating.

Development of traffic controls renders the intent of the 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 requires 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 so as to manage local traffic flow and safety conditions. Both 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 in compliance with both traffic regulations—the body of traffic law applicable within the jurisdiction(s) in which the vehicle is operated—and the local traffic controls. This is an important distinction, in that the regulations are in practice implicit to those operations and may not be locally marked or signed. Regulations of this type might include rules such as 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

[31] For example, "Vehicles and Traffic Safety," *Code of Federal Regulations (annual edition). Title 36: Parks, Forests, and Public Property. Part 4: VEHICLES AND TRAFFIC SAFETY,* Monday, July 1, 2019.

emergency workers are present. Vehicle operations are generally also subject to local custom where actions are based on standards of reasonableness or implicit negotiation between vehicle operators.

Law enforcement operates both 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 judgement.

The forms of traffic regulations as they exist in the current world of human-driven vehicles, and as they will need to persist into a world of ADS and AVs, are represented in the Figure 4 diagram by ellipses.

The Uniform Vehicle Code (UVC) provides a set of traffic regulation on which State and local traffic codes may be based. It represents a historical consensus on traffic regulation, but has no legal standing and is not normative for regulations.

"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 Manual on Uniform Traffic Control Devices (MUTCD) is a common national standard for markings and signage on roadways. It both comes from and is used as a reference for development and application of controls by State and local agencies. The MUTCD is published by the Federal Highway Administration (FHWA) but has legal standing only insofar as adopted by the State and local agencies.

"Traffic controls" represent the types of regulatory markings and signs on the roadways that may be needed to assure safety and preserve mobility in traffic movement. In this context, they represent the types of traffic controls based on the MUTCD with State and local variations.

"Deployed traffic controls" are markings and signs of various types as they are deployed on the roadways in particular locations for particular modes of operation at particular times.

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 of the interviews provided insightful observations ending in questions as to how the issues might unfold with ADS development and deployment.

Traffic Code Practitioners

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

> *"There is no testing a law. You just have to write the law and see what happens."*
>
> *– Traffic code practitioner in interview*

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 custom 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 Developers

Traffic control developers specify standards for traffic control indications—pavement markings and signage—on the roadways. This specification occurs at a national scale in the development of the MUTCD as facilitated by FHWA, but becomes part of the body of State traffic regulations by reference within the statutes to the particular State traffic control codes. This is a critical 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 MUTCD is updated relatively infrequently—about every 10 years—and in arrears of traffic devices having already been installed in some locations. The innovations are collected by consensus from State and local traffic control deployment experience for standardization and publication. Controls for work zone scenarios are the fastest growing section of the MUTCD.

Optional guidance is 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.

Infrastructure Owner-Operators

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

The unstated presumption on traffic control deployments 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 6-inch 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. Sign databases are not always well maintained by State or local agencies, and the number of traffic signs is higher than generally appreciated.

It was also noted that deployment of traffic controls 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 the 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 development and deployment of advanced driver assistance systems (ADAS) through automation Level 3, and for ODDs not explicitly automated at Level 4. ADS on vehicles operating at automation Levels 4 and 5 will fully subsume this responsibility for their designated ODDs.

Perspectives on and needs for the regulations data framework from the ADS itself are discussed under the ADS developers section below.

Enforcement Agencies

In the context of the regulations framework, enforcement agencies include those that monitor roadways for violations and those that adjudicate perceived violations in the traffic courts. Roadway traffic law enforcement is generally performed by municipal police forces, sheriff departments, and State police or highway patrol. Some locations have enacted automated enforcement means such as red-light cameras and speed sensors, some of which provide only warnings, and some of which issue citations for violations. The traffic court systems become involved when drivers question citations, whether by officers or automated means.

Interviewees noted that the 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 (AAMVA) has issued some initial guidance on the subject and continues to be in conversation with ADS developers. Current topics of interest include, for example, whether AVs should provide an indication external to the vehicle that it is being operated by an ADS. 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.

Automated Driving System Developers

ADS developers are any of those researchers and programmers working on behalf of academic institutions, governmental agencies, technology companies, and vehicle manufacturers involved in ADS development. There is a tremendous diversity of interest in and approaches to ADS development within this community. The sample of interviews conducted for this study ranged from start-up tech companies to large multinationals, and from tier-one suppliers to light- and heavy-vehicle manufacturers. All interviewees were clear about their need for 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 would prefer a harmonized understanding of traffic regulations across jurisdictions to enable the development of 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 expression of 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 they would encounter along the roadways. ODDs have thus far been identified and described by individual ADS development teams 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 thread of discussion was around questions of how regulations depending on a human vehicle operator might apply to ADS-equipped vehicles. This seemed to be a greater concern for ADS-equipped heavy vehicles—for example, with laws about putting reflective triangles out 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-vehicle (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 for 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 guidance on testing and certification of ADS behavior for the intended ODDs.

CHAPTER 4. TRAFFIC REGULATION DATA EXCHANGE CONCEPTS

TRAFFIC REGULATIONS DATA AND THE UNIFORM VEHICLE CODE

Although the Uniform Vehicle Code (UVC) is not prescriptive for traffic regulations across the United States, it is archetypical and can be used to identify the essential elements of traffic control regulations. Chapter 1 begins by defining the words and phrases for the transportation system users, vehicle types, roadway types, and other elements used in the regulations. Chapter 11, Rules of the Road, describes in its individual sections the regulations for the interactions of road users with each other, the roadway, and the flow of traffic. The intended readers include human drivers, regulators, administrators, and enforcement officers, so the regulations implicitly describe the interactions between those user roles. They 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, the UVC Section 11–310 on “Following too closely” states, in part, that: “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.”[32]

The UVC does not, however, provide or suggest interpretations of or measurable values for “more closely than is reasonable and prudent” or “due regards 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.

PROPOSED TRAFFIC REGULATION DATA ELEMENTS AND DEFINITIONS

Figure 5 depicts entities and relationships involved in regulating automated driving systems (ADS). This section first describes the entities and then the inter-relationships among them.

State and local government entities enact and enforce traffic statutes. As infrastructure owner-operators (IOO), they interpret traffic regulations and accordingly deploy traffic control signals and signs. State and local governments have jurisdictions that can be defined by geographical boundaries and enact statutes that can be interpreted as 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 is defined by one or more boundaries.

A boundary encloses a jurisdiction and is defined by a set of geo-coordinates. 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).

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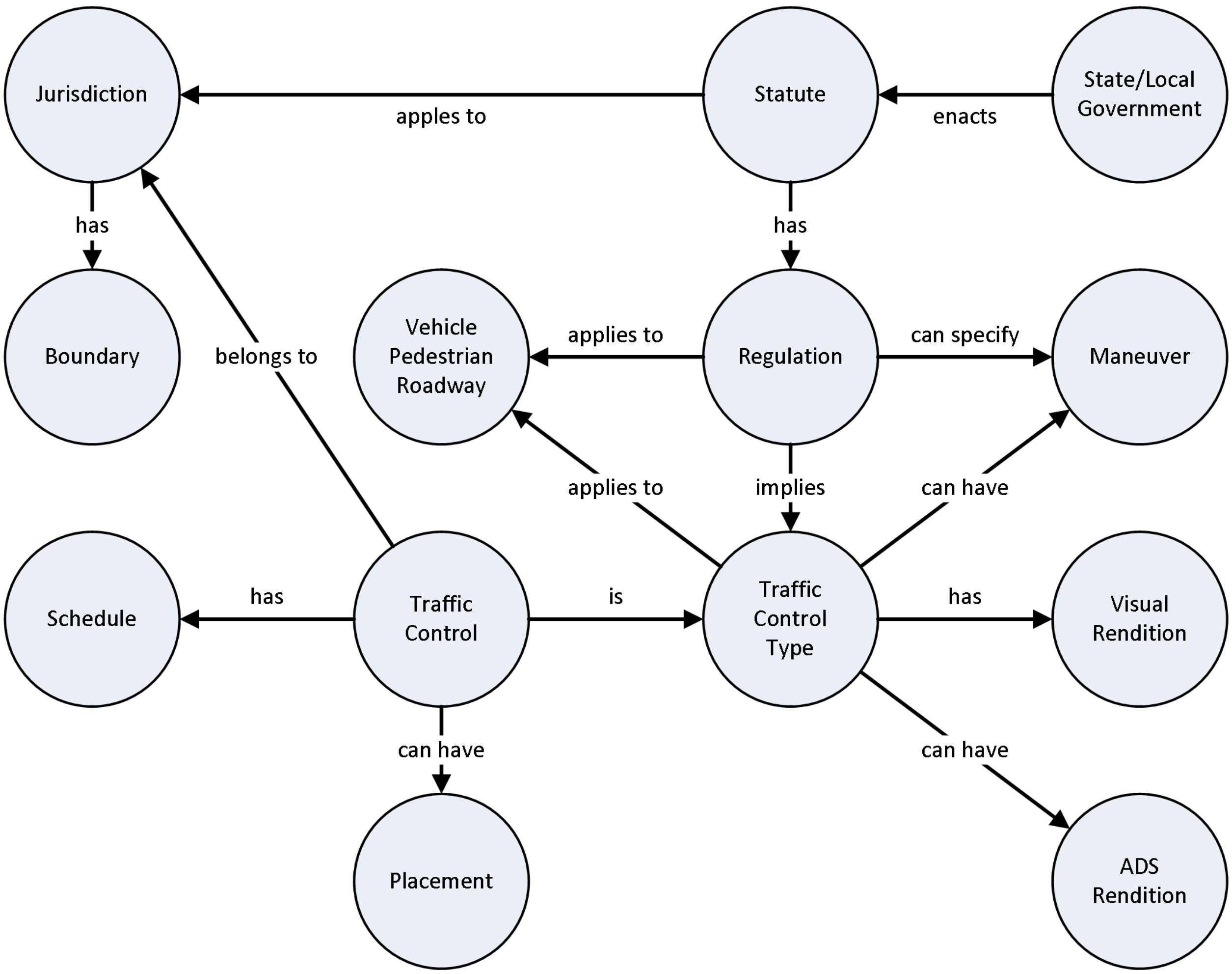
[32] *Uniform Vehicle Code* (Alexandria, VA: National Committee on Uniform Traffic Laws and Ordinances, 2000), 134.

A statute is an element of law enacted by a legislative body that sets forth general propositions that can be applied to specified situations.

Regulations codify the particular situations, actors, actions, and constraints that the statutes require. Regulations can help inform the traffic control types, but the behaviors that result from the traffic control 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.



Source: FHWA.

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

The Manual on Uniform Traffic Control Devices[33] (MUTCD) defines traffic control types. Traffic control types apply to classes of transportation infrastructure users and facilities, and enable or restrict maneuvers. They specify the classes and types of controls that may be deployed

[33] FHWA, Manual on Uniform Traffic Control Devices for Streets and Highways (Washington, DC: USDOT, 2012).

within a jurisdiction to enact the regulations. They define constraints on driving behavior such as maximum speed for commercial tractor/trailers. They 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 flagman.

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 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, school children, and people who have a physical impairment. Roadway classes include freeways, highways, arterials, and neighborhood roads.

Maneuvers are longitudinal and lateral vehicular movements such as passing, stopping, merging, and turning at intersections. Regulations can allow, disallow, or constrain maneuvers under particular conditions.

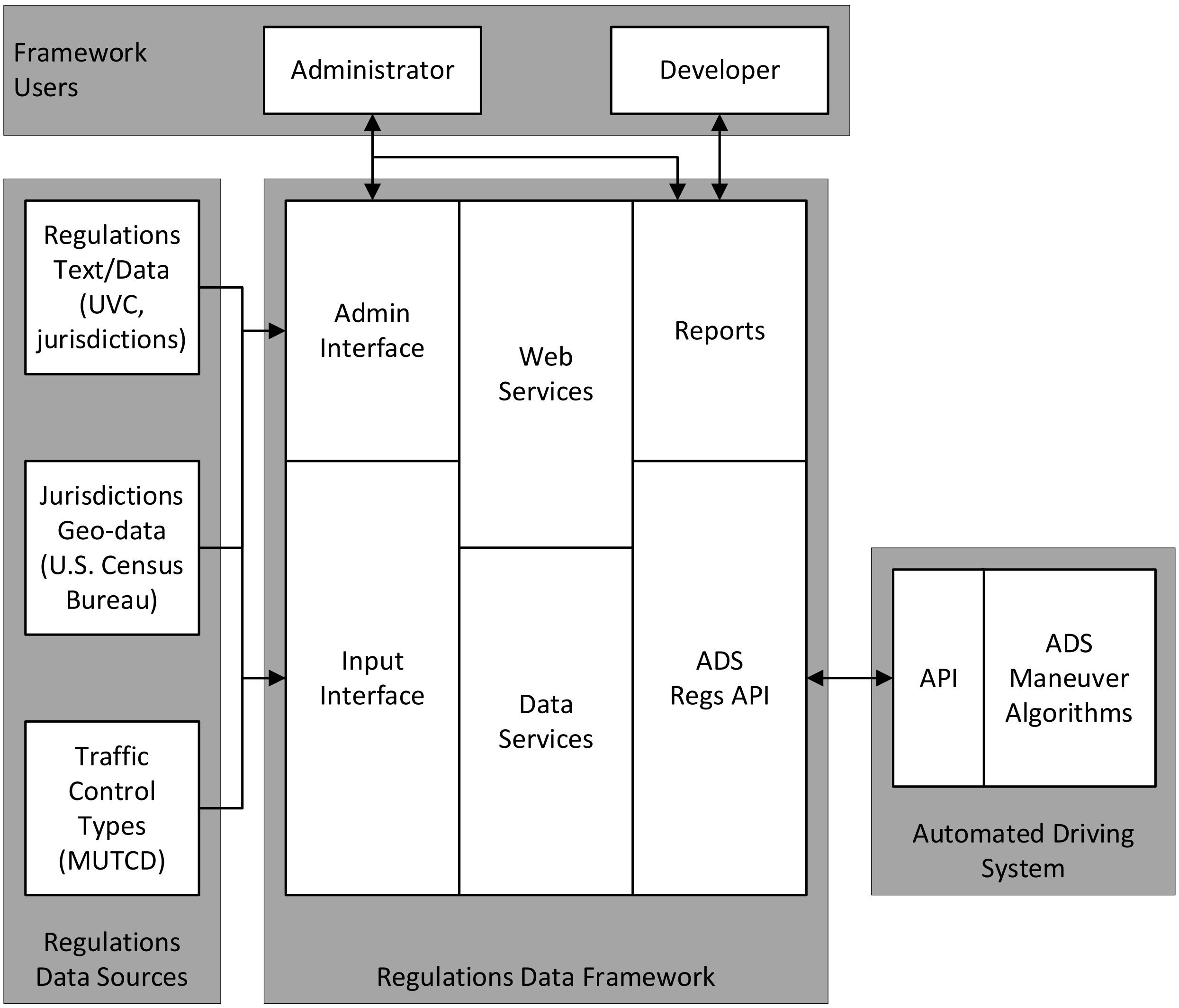
Traffic controls are instances of traffic control types deployed to particular locations on the roadway network. Traditional traffic controls typically involve visual markings, signs, and signals. They inherit the properties defined by their traffic control types, including their visual and ADS renditions. 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 a day for operations, or cycles of operation (e.g., traffic signal and ramp meters). The schedule for a maximum speed allowed in a school zone, for example, could be as complex as weekdays between 2 and 4 p.m. bounded by the beginning and ending 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.

PROPOSED TRAFFIC REGULATION INTERFACES

Based on the stakeholder needs and the use cases discussed in this document, the system described below is proposed to enable storage and retrieval of regulations, regulations interpreted as affected actors and expected maneuvers, 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 proposed 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: FHWA.

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 requires 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. For the proposed model to operate correctly, some underlying information sources are necessary to enable it. In the case of named jurisdictions and their boundaries, the United States Census Bureau publishes legal boundaries and names, and their related Federal Information Processing Standards (FIPS), Zone Improvement Plan (ZIP), and geo-coordinate boundaries in shape file (SHP) format. Visual representations of signs from the MUTCD are published by the Federal Highway Administration (FHWA) as downloadable Encapsulated PostScript (EPS) and portable document format (PDF) files. Pedestrian, vehicle, and roadway classifications and allowed maneuvers can also be derived from the MUTCD 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 (HTML) 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. ADS renditions will be generated by the traffic control data.

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 a latitude, longitude, elevation, and orientation and applicable approach vectors.

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

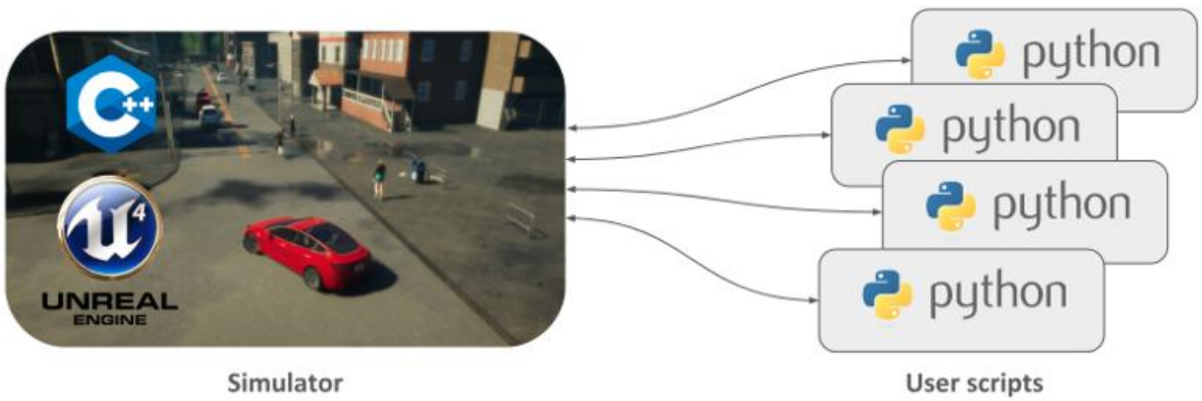
Even a sparsely-populated ADS regulation data framework provides a valuable basis for AV-related information. The proposed application could be used to select a jurisdiction and be presented with a list of regulations and their corresponding interpretations, a list of traffic control types and their visual presentations, or a list of traffic control instances and their 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.

SIMULATIONS METHODOLOGY

Validating a conceptual regulations data framework does not necessarily need physical ADS-equipped vehicles operating on public roadways. The intent in this project is to develop the concept to a level at which it can be demonstrated for select use cases within a defined and documented operational design domain (ODD) using a small sample data set in a simulated ADS-roadway environment. The simulation environment may then have specific interfaces that need to be fulfilled to complete the demonstration. The ADS regulations data framework proposed in the prior section will provide data for those use cases by means of the simulator application programming interfaces (API). This section briefly introduces the CARLA simulator for autonomous driving, to be applied in this context to ADS-equipped vehicles.

CARLA is an open-source platform that supports independent research in and development of AV environments and behaviors. It enables developers to build detailed models of an operations environment, actors (e.g., vehicles and pedestrians), and behaviors. CARLA uses the OpenDRIVE® standard (version 1.4, as of the date of this report) to define the roadway environment and the Unreal Engine to simulate vehicle operations. The simulation controls use an API accessible in Python® and C++.

A complete CARLA simulation consists of client use case models, the server physics computations, and the user scripts that relate the two. The server components deal with the simulation rendering, computations, world-state, and actor. The client manages the behavioral logic of the use case actors and the roadway setting.



Source: CARLA.

Figure 7. Illustration. Relationship between CARLA core simulator and Python® application programming interfaces.[34]

As described in the CARLA documentation,[35] key features and elements of CARLA include the following:

- **Traffic manager**. This component models the roadway environment using realistic physical behaviors of the ADS-equipped vehicle and other vehicles in the surrounding traffic.
- **Sensors**. Cameras, red-green-blue (RGB) images, radar, light detection and ranging (LiDAR), and other sensors are modeled as specific actor objects attached to vehicles.

[34] "CARLA," CARLA Simulator, accessed May 18, 2020, https://carla.readthedocs.io/en/latest/start_introduction/.

[35] "CARLA," https://carla.readthedocs.io/en/latest/start_introduction/.

This method enables data captured by those sensors in the model to be provided to the simulated vehicles and to be retrieved as output from the simulation.

- **Robot Operating System™ (ROS) bridge and Autoware implementation**. The CARLA project provides integration with other development, simulation, and machine learning environments with bridges to the ROS and Autoware.

- **Open assets**. The CARLA architecture enables modeling of roadway environments, including weather, through a library with templates for simulation actors and conditions.

- **Scenario runner**. CARLA's scenario component enables developing route models that can run iterative simulations to feed machine learning processes for ADS.

Data can be collected directly from the client in real time through the API. The API provides access to the simulated sensors and to measurements associated with the state of the environment, such as vehicle location, velocity, acceleration, traffic signal state, lane locations, and speed limits at any location. These measurements are essential to modeling realistic behavior.

Traffic laws and regulations can be modeled as part of the use case traffic environment through Python APIs and sent directly to the subject ADS-equipped vehicles. The vehicle control algorithms (i.e., motion or trajectory planning) will use this information to plan and implement maneuvers that comply with traffic laws and regulations as part of the dynamic world model created by the environment sensing module.

CHAPTER 5. USE CASES

Use cases are used to describe the applications and interactions of stakeholders with the proposed framework, including its relationship to potential operational design domains (ODD) for the ADS-equipped vehicles. Use cases generally need to address perspectives of specific stakeholder groups (e.g., automated driving system [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 would be that the system in question is the data framework for traffic regulations. That may, however, 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 automated vehicles (AV). A more nuanced view of the potential use cases has (at least) two layers: use cases for the framework itself, addressing the perspectives of providers as well as users of the regulations data, and use cases for the regulations data within the framework, focused on the needs of ADS developers. Uses 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 is not useful.

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

1. Early-stage ADS and AV development is focused on research and demonstration in operational design domains (ODD) selected by the developers. 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 around capture of and access to the enacted traffic regulations for jurisdictions in which the ADS intends to be operating.

2. Traffic controls serve as reminders of and specific pointers to traffic regulations as they apply on the roadways. ADS operations on public roadways will need to have at least sufficient awareness of traffic controls so as to limit their 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 that they might encounter and need to understand in those jurisdictions. This library then serves as a reference for further expansion of ODDs to include a broader range of maneuvers and control types.

3. 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 essentially the concept behind the MAP and Signal Phase and Timing (SPaT) messages defined in the Society of Automotive Engineers (SAE International) J2735™ standard for vehicle-to-infrastructure (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.

4. Traffic statutes as written and enacted in the State and local traffic codes use natural human language to describe their intents. Interpreting those regulations for an ADS must render that intent into a set of 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.

Use cases will be used later in this project to support additional tasks. A demonstration of the framework interfacing with an ADS simulation will address use cases for the framework as they apply to a specific ODD to be defined for that demonstration. Developing a test plan for use in a subsequent framework pilot deployment will need to consider the use cases as part of that planning.

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 pre-condition, 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.

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 Manual on Uniform Traffic Control Devices (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 pre-condition, 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 controls with the names of the deployed traffic controls, 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 pre-condition, the deployed traffic controls 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, actor(s), and applicable constraints equivalent to regulations within a jurisdiction or applicable at a location. Requests are anticipated to come from automated systems. As a pre-condition, 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 the 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 proceeded 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 that they would eventually address all regulations, use cases, and development needs. As such, it is not possible in the scope of this effort to provide a complete mapping of use cases to ODDs. However, it does appear that use cases based on regulations can be allocated and considered 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 is primarily in the extents and limits placed on the maneuvers, not on the mechanics. Making a right turn at a signalized intersection is fundamentally the same driving task regardless of whether the maneuver takes place 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) within Chapter 11 of the UVC.

Table 1. Classes of use case based on the Uniform Vehicle Code.

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

Source: FHWA
Ch. = chapter, DUI = driving under the influence, MUTCD = Manual on Uniform Traffic Control Devices, UVC = Uniform Vehicle Code.

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. The key questions are: Can the ADS determine constraints on maneuvers (regulations) applicable to the jurisdiction in which it is operating at the moment of decision?

Can the ADS recognize the traffic controls it encounters in its local operations? These and other similar questions will become part of the basis for the proof-of-concept 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/server to determine the speed limit with which it needs to comply. The ADS will then change the vehicle speed as appropriate 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.

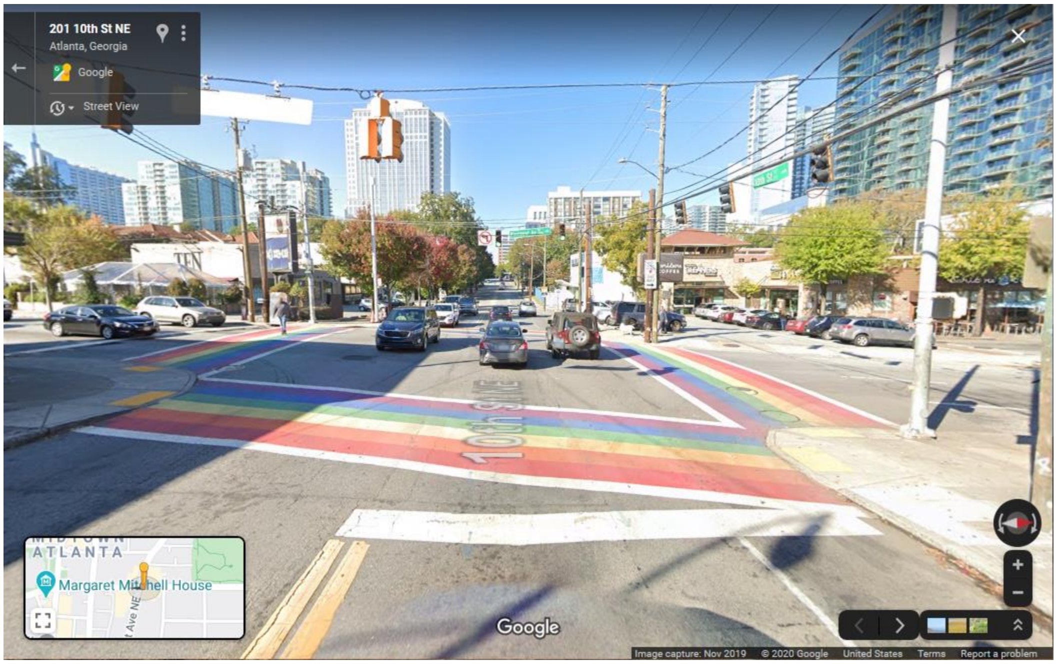
Comply with Right-Turn-on-Red Regulations at Signalized Intersections

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 Non-standard 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 8). 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.



© 2019 Google Maps™.

Figure 8. Screen Capture. Non-standard pedestrian crosswalk in Atlanta, Georgia.

Comply with Non-specific 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, and a law enforcement officer could pull over an ADS if the office 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."

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 there stop signs being extended by the bus? Are there 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?

CHAPTER 6. IMPLICATIONS FOR IMPLEMENTATION

This concept of use (COU) describes the need and concepts for the design of a traffic regulations framework to support automated driving system (ADS) development and deployment. However, the implications of those concepts and design may represent challenges for prototype implementation. This section assesses the implications of the proposed approach relative to design and deployment, testing, system operations and maintenance, revision control, system performance measures, security and privacy, and future considerations for new technology.

DESIGN AND DEPLOYMENT

Vehicle Function Regulations

Some traffic laws imply required vehicle equipment or functions. For example, some States require the use of windshield wipers when it rains, which implies that the vehicle must be equipped with wipers. The study authors assume that the original equipment manufacturer (OEM) responsible for the vehicle using the ADS will comply with all Federal motor vehicle safety standards (FMVSS) or exemption specifications for safety systems, equipment, and performance as the National Highway Traffic Safety Administration (NHTSA) requires. However, FMVSS are being updated in response to ADS needs, which makes the FMVSS another evolving list of requirements that OEMs must track as changes are made. This is significant for the demonstration use case only to the extent that the vehicles are equipped as needed to complete the use case.

Regulations Data Access and Collection

As described previously, State traffic codes are generally available and able to be collected from the regulatory sources, though not necessarily in forms convenient for developing a database. Local government codes are unlikely to be so readily available and will present additional challenges for identification and collection. Data on regulatory traffic controls within a jurisdiction are significantly less available in database form, though the traffic controls are generally observable in field deployments. As such, a prototype demonstration may be constrained to specific examples of regulations and their variation across jurisdictions.

Limitations in Matching Regulations and Traffic Control Devices with Automated Driving System Behavior

Traffic codes are written for human interpretation and application and may face challenges in being interpreted for ADS. The interpretation will need to identify specific driving tasks and maneuvers and different roadway environments and scenarios in which the regulations apply, and specify the operational limits associated with those tasks. Similarly, traffic control devices are currently deployed as marked or signed indications along roadways. Conceptually, an ADS will need to be able to identify the applicable regulations and roadside control devices from its own imaging systems, static controls associated with mapped locations, or static and dynamic control data provided in infrastructure-to-vehicle (I2V) exchanges. For use case demonstrations, any traffic control devices to be recognized by the ADS will need to be catalogued and known to the vehicle for matching with its perceptions, mappings, or traffic control messages.

Coordination across Jurisdictions

Just as human drivers need to know the rules of the road in the various jurisdictions through which they travel, an ADS will need to be aware of its current location and the applicable regulations. In practice, much of the local variability will take the form of signed controls on the roadway. Some allowed behaviors and constraints, however—like right turn on red or speed limits based on road classification—are permissible unless otherwise precluded by an explicit traffic control indication. Use case demonstrations will need to accommodate and demonstrate the regulations framework's requirements for working across jurisdictions.

TESTING

Technology testing is an integral part of deployment and represents the process of analyzing a system or component by providing defined inputs and comparing the results with the desired outputs.

In this context, testing can have variable degrees of manual testing and automation. Manual testing requires human input, analysis, and evaluation. Automated testing uses automated steps to reduce human errors in the testing process. These errors may occur due to humans getting tired of a repeated process, while automated testing will not miss a test by mistake. The automated test program will also provide the means of accurately storing test results, which can be fed into a database that provides necessary statistics on how the new data system is performing. Automated testing can detect errors in the database, which may have a major impact on ADS traffic law compliance and affect ADS behavior and safety.

Objectives of automated testing are as follows:

- Perform repetitive and tedious tasks to accurately reproduce tests.
- Validate requirements and functionality at various levels.
- Simulate multiple users exercising system functionality.
- Execute more tests in a short amount of time.
- Reduce test team head count.

SYSTEM OPERATIONS AND MAINTENANCE

There are many independent and overlapping jurisdictions with governing bodies that can independently enact statutes and interpret regulations to facilitate the safe use of common transportation infrastructure. The result is that an ADS regulations system will benefit from being decentralized, regardless of choosing traditional relational database management with replication, durable stream processing, blockchain distributed ledger, or other similar technology.

Diffusing system implementation provides valuable benefits. No single agency is burdened with the expense of hosting and maintaining communication infrastructure as well as propagating data updates. The large complex problem of interpreting regulations is broken into the optimal effort encouraging participation. System responsiveness and resilience is maximized by keeping information consumers as close as possible to information producers with no single points of disruption.

REVISION CONTROL

The ADS regulations system contains information elements that can change somewhat frequently (traffic control instances and traffic control types), and much less frequently (statutes, regulations, the Manual on Uniform Traffic Control Devices [MUTCD], published traffic engineering standards). The mechanism to handle changes is the same. System records maintain a time range over which they are considered valid and references to previously superseded entries. There is also a transaction log that stores what information was changed, when it was changed, and who changed it.

Developed software follows common open-source version-control practice. Design documentation, deployment and administration documentation, and source code will be uploaded and maintained through the Open Source Application Development Portal (OSADP) GitHub process.

SYSTEM PERFORMANCE MEASURES

Web applications handling millions of transactions every day are commonplace. Human-scale interaction with the system will meet present day user expectations of a few seconds to update data, and receive report output. Timing for user interface elements can be monitored using many available log analysis tools.

An estimate of record count can be determined from the number of jurisdictions, number of regulations per jurisdiction, and number of traffic controls. If an average of three traffic controls (i.e., actuated signal, speed limit sign, mile marker, left- and right-lane markings) exist per road mile in each direction, then approximately 24 million total traffic controls exist. On the low end, there could be 50 jurisdictions with 1,000 regulations totaling 50,000 records. On the high end, there could be 10,000 jurisdictions with 10,000 regulations totaling 100 million records. Current transaction processing software and data storage hardware is handily capable of sustaining 200 million records.

The key system performance indicator is more closely related to the instantaneous demand for traffic regulation information by ADS, i.e., queries per second. It would be truly spectacular if 300 million vehicles simultaneously requested 200 million records—and totally unnecessary. Distributed deployments mitigate this situation.

ADS-equipped vehicles in New Mexico do not need traffic control information about West Virginia, for example. Each ADS-equipped vehicle does not even need every traffic control defined by a given jurisdiction. An automated vehicle (AV) does need traffic control information for its planned route, which it monitors many times per second but updates every few minutes.

System implementations will support delta queries that quickly determine what has changed since the ADS's last local database update, and subsequently deliver the reduced set of traffic control differences. In a simplistic model, if an average response is 100 kilobit (Kbits), then one service node having 1 gigabit per second (Gbit/s) communication bandwidth can handle 10,000 traffic control queries per second. This is the equivalent of meeting the immediate needs for every vehicle within the State of Virginia or within New York City in under 10 minutes, and is well within the performance capabilities of contemporary online transaction processing software.

SECURITY AND PRIVACY CONSIDERATIONS FOR AN AUTOMATED DRIVING SYSTEM TRAFFIC REGULATION ECOSYSTEM

For any advanced data system, many of the primary ownership and maintenance (O&M) considerations involve the management and security of data. The Federal Highway Administration (FHWA) Reliability Data Guide's section on Data Ownership and Maintenance[36] presented a sample list of fundamental considerations likely to govern O&M levels of effort and expense:

- Who will pay to collect, store, and share the data?
- Who (if anyone) can sell the data, and to whom may it be sold?
- Are there any privacy issues in the data that must be addressed?
- Who is allowed to access the data, and what data may they access (all of it? only a subset?)?
- What purposes are the data allowed to be used for (e.g., if they are collected for analysis purposes only, could they also be used for enforcement?)?

The *Real-Time Data Capture and Management State of the Practice Assessment and Innovations Scan*[37] addressed issues related to data capture, data management, archiving, and sharing collected data to encourage collaboration, research, and operational development and improvement. The scan documented the following best practices for access, security, and privacy:

- Generally, the holder of the data controls access to them. Within the transportation and logistics community, this access is carefully controlled.
- There are systems in place that ensure that data can be accessed only by the intended people and only to the degree that they need it. The type of data used by the transportation and logistics industry makes it extremely sensitive, with disastrous consequences for a business if accessed by persons with malicious intentions.
- Usually, data access is password-protected, and the following is true:
    - Because data generated within the logistics systems are often financial, strong encryption is placed on such data when they are sent.

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[36] https://www.fhwa.dot.gov/goshrp2/Solutions/Reliability/L02_L05_L07_L08_C11/Reliability_Data_and_Analysis_Tools.

[37] SAIC, Real-Time Data Capture and Management State of the Practice Assessment and Innovations Scan: Lessons from Scan of Current Practices, (Washington, DC: FHWA, 2011).

    - However, several applications can retrieve aircraft and vessel tracking data, often with other identifying information. The security clearance or password protection to access data through these applications is often minimal.

- The protection of data sources is extremely important. In the search engine industry, it is so heavily protected that there is not even disclosure of how exactly it is protected.

The scan documented the following best practices for data storage and backup:

- Frequent backups and off-site storage are typical.
- Preventative maintenance should be performed regularly.
- Careful consideration should be devoted to determining how much and for how long data should be stored. In aviation, for instance, data are kept for a relatively short time frame because the need is for real-time rather than historical information. At the same time, data can be available for revision if there is an incident to investigate.

The scan documented the following best practices for operations and maintenance:

- Deployment should be started on a reasonable scale, such as implementing in a small geographical area or using easily manageable data.
- Multiple servers should be used to distribute real-time loads. Several technologies enable this load distribution.
- It is important to consider determining the needed resolution or granularity of the data. This may vary depending on the context and use of the data.
- It is necessary to determine what is critical to communicate and what is not. For instance, railroad and airline alert systems only collect the necessary data that can alert an operator of a particular problem.

The scan documented the following best practice for critical failures:

- A common issue is that correcting a problem is often dependent on a single person, meaning its solution depends on the person's availability. It is therefore important to have staff available around the clock to solve potentially catastrophic failures. The higher labor cost is a necessary expense if the system needs to be highly available at all times.

FUTURE CONSIDERATIONS

As described in the introduction to this COU, the field of ADS is in its early stages of development. Attention to regulations for ADS-equipped vehicles has been largely structured around allowances and permits for testing in various jurisdictions. Legal reviews of the applicability of existing rules of the road to AVs are just beginning.

The ADS regulations framework described in this COU will therefore be designed to link directly back to the actual traffic regulations in the contributing jurisdictions to provide traceability and a path for adding new regulations as they are enacted.

The framework is similarly designed to facilitate adding new traffic control types and deployments, should those become desirable or necessary. The components that catalog deployed traffic control elements are designed to support a virtual traffic controls infrastructure if that interface were to be requested by ADS developers and deployers.

Parametric interpretation of the traffic statutes is included in the framework design for prototype demonstration and for future development. A fully implemented translation of Federal, State, and local statutes into parametric forms may be achievable, but it is beyond the scope of this prototype effort.

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