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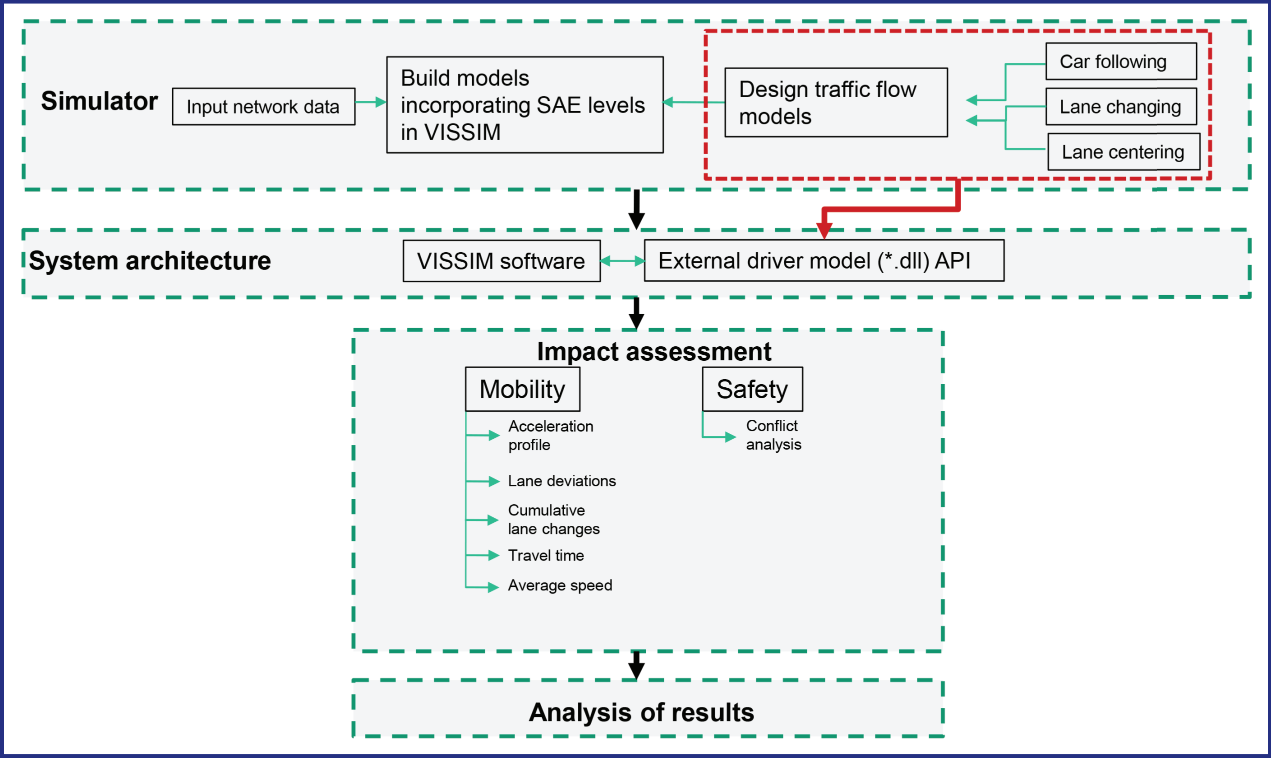
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Strategic and Tactical Guidance for the Connected and Autonomous Vehicle Future



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SPR-4123• Report Number: FHWA/IN/JTRP-2019/02 • DOI: 10.5703/1288284316879

RECOMMENDED CITATION

Ukkusuri, S., Sagir, F., Mahajan, N., Bowman, B., & Sharma, S. (2019). *Strategic and tactical guidance for the connected and autonomous vehicle future* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/02). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316879

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Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2019/02	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Strategic and Tactical Guidance for the Connected and Autonomous Vehicle Future		**5. Report Date** January 2019 **6. Performing Organization Code**
7. Author(s) Satish Ukkusuri, Fasil Sagir, Nishtha Mahajan, Benjamin Bowman, Salil Sharma		**8. Performing Organization Report No.** FHWA/IN/JTRP-2019/02
9. Performing Organization Name and Address Joint Transportation Research Program (SPR) Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-4123
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Autonomous vehicle (AV) and connected vehicle (CV) technologies are rapidly maturing and the timeline for their wider deployment is currently uncertain. These technologies are expected to have a number of significant societal benefits: traffic safety, improved mobility, improved road efficiency, reduced cost of congestion, reduced energy use, and reduced fuel emissions. State and local transportation agencies need to understand what this means for them and what they need to do now and in the next few years to prepare for the AV/CV future. In this context, the objectives of this research are as follows:

1. Synthesize the existing state of practice and how other state agencies are addressing the pending transition to AV/CV environment
2. Estimate the impacts of AV/CV environment within the context of (a) traffic operations—impact of headway distribution and traffic signal coordination; (b) traffic control devices; (c) roadway safety in terms of intersection crashes
3. Provide a strategic roadmap for INDOT in preparing for and responding to potential issues

This research is divided into two parts. The first part is a synthesis study of existing state of practice in the AV/CV context by conducting an extensive literature review and interviews with other transportation agencies. Based on this, we develop a roadmap for INDOT and similar agencies clearly delineating how they should invest in AV/CV technologies in the short, medium, and long term. The second part assesses the impacts of AV/CVs on mobility and safety via modeling in microsimulation software Vissim.

17. Key Words autonomous vehicles, connected vehicles, transportation authorities, impact assessment, microsimulation	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 87	**22. Price**

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EXECUTIVE SUMMARY

STRATEGIC AND TACTICAL GUIDANCE FOR THE CONNECTED AND AUTONOMOUS VEHICLE FUTURE

Introduction

Autonomous vehicle (AV) and connected vehicle (CV) technologies are rapidly maturing, but the timeline for their wider deployment is currently uncertain. State and local transportation agencies need to understand what this means for them and consider what they need to do now and in the next few years to prepare for the AV/CV future.

The objectives of this research are to do the following:

1. Synthesize the existing state of practice for AV and CV vehicles and analyze how other state agencies are addressing the pending transition to an AV/CV environment.
2. Estimate the impacts of an AV/CV environment on traffic operations, including headway distribution and traffic signal coordination, traffic control devices, and intersection crashes.
3. Provide a strategic roadmap for INDOT to prepare for and respond to potential issues.

Findings

- It is imperative for INDOT to join pooled fund studies and the smart coalition. In addition, INDOT should prioritize the preparation of its infrastructure networks for AV/CV technology by installing clear lane markings and DSRC radios on traffic signals and ensuring the standardization of road design and signage. We also recommend testing both direct short-range communications (DSRC) and fifth-generation wireless (5G) on a single corridor to understand the pros and cons of both.
- Based on AV modeling in VISSIM, we saw an increase in average vehicle speeds near merging sections (at least 1.2%) with percentages as low as 20% of SAE 1 and above.
- For SAE 2 onward, we observed a decrease in the tendency of AVs to deviate from the center of the lane (50% for SAE 2 and 87% for SAE 4), which indicates that lane widths can be decreased in an AV-only traffic scenario.
- We found that outside operational design domain (ODD) conditions (such as unclear pavement markings) significantly affect mobility with SAE Level 4 and saw a 50% drop in average speed with SAE 4 compared to a fully autonomous SAE 5.
- From a traffic volume analysis of the I-70 and I-465 freeway interchange with full saturation of different SAE levels, we observed a significant increase in volume throughput (33% for SAE 1 and 150% for SAE 5), indicating significant increases in road capacity.
- Conflict analysis of AVs indicates a decrease in the number of conflicts based on time to collision (30% for SAE 1 and 90% for SAE 5), implying an increase in safety.
- We observed that benefits of intentional platooning with cooperative adaptive cruise control (CACC)–equipped vehicles only materialize with higher percentage composition of CVs and higher flow rates. This may warrant introducing dedicated lanes for platoon formation when CACC penetration is low and/or flow rate is low.
- We observed that the most common platoon size is 2, but platoon sizes as large as 13 were also observed for 90% penetration and above with ad-hoc platoon formation technique at a flow of 800 veh/h/lane. This indicates the need for modifications in present traffic management techniques to allow for smooth movement of large groups of vehicles moving together.

Implementation

Based on this synthesis study, we prepared a roadmap for INDOT divided into short-term, medium-term, and long-term objectives to incorporate AV/CVs on Indiana's roadways. Important considerations that to take into account when investing in an AV/CV future were also listed.

To understand the impacts of AV/CV on mobility and safety, we developed microsimulation software—VISSIM-based simulation models—that can be further employed to understand the following:

- Impacts of AV-only lanes for trucks and cars
- Impacts on mobility and safety due to a mix of AV classes (cars and trucks)
- Impacts of autonomous intersections
- Assessment of surrogate safety measures for AVs
- Mobility and safety impacts of truck only platooning
- Impacts of dedicated lanes for platoons
- Assessment of CV performance with SPaT messages

We also developed a VISSIM-based microsimulation framework to simulate connectivity and identify the different features in traditional versus CV-based signal control. Any algorithm of interest to INDOT can be fully integrated and tested in a future project using this framework.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

4G	Fourth Generation Wireless
5G	Fifth Generation Wireless
5GAA	5G Automotive Association
AAMVA	American Association of Motor Vehicle Administrators
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ACS Lite	Adaptive Control Software—Lite
ADOT	Arizona Department of Transportation
API	Application Program Interface
ASCII	American Standard Code for Information Interchange
ATIS	Advanced Traveler Information Systems
AV(s)	Autonomous Vehicle(s)
BARC	Berkeley Autonomous Race Car
BSM(s)	Basic Safety Message(s)
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
Caltrans	California Department of Transportation
CAV(s)	Connected and Autonomous Vehicle(s)
CCH	Control Channel
COM	Component Object Model
CV(s)	Connected Vehicle(s)
C-V2X	Cellular Vehicle-to-Everything
CVASD	Connected Vehicle Applications and Supporting Documentation
CVDP	Connected Vehicle Deployment Program
DLL	Dynamic Link Library
DMV	Department of Motor Vehicles
DOT(s)	Department(s) of Transportation
DR	Deceleration Rate
DSRC	Direct Short-Range Communications
EDM	External Driver Model
EIDM	Enhanced Intelligent Driver Model
FCC	Federal Communications Commission
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standard
GPS	Global Positioning System
HAV(s)	Highly Autonomous Vehicle(s)
I2I	Infrastructure to Infrastructure
I2V	Infrastructure to Vehicle
IDM	Intelligent Driver Model
IDOT	Illinois Department of Transportation
IEEE	Institute of Electrical and Electronics Engineers
IMA	Intersection Movement Assist
IMU	Inertial Measurement Unit
INDOT	Indiana Department of Transportation
IQR	Inter Quartile Range
ITS	Intelligent Transportation System
ITS JPO	Intelligent Transportation Systems Joint Program Office
JTRP	Joint Transportation Research Program
LCW	Lane Change Warning
LIDAR	Light Detection and Ranging
MAC	Media Access Control
MAP	Intersection Map
MAX D	Maximum Deceleration
MAX Delta S	Maximum Absolute Speed Difference
MDSS	Maintenance Decision Support System
MMITSS	Multi-Modal Intelligent Traffic Safety Systems
MRCDS	Minimal Risk Condition Desired Speed

NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
NYC	New York City
NYSDOT	New York State Department of Transportation
OBE	On-Board Equipment
ODD	Operational Design Domain
ODOT	Oregon Department of Transportation
ODOT	Oregon Department of Transportation
OEM(s)	Original Equipment Manufacturer(s)
PET	Post Encroachment Time
PSID	Provider Service Identifier
RADAR	Radio Detection and Ranging
RHODES	Real-time Hierarchical Optimizing Distributed Effective System
RSE	Roadside Equipment
SAE	Society of Automotive Engineers
SC	Signal Controller
SCH	Service Channel
SCOOT	Split Cycle Offset Optimization Technique
SPaT	Signal Phasing and Timing
SSAM	Surrogate Safety Assessment Model
THEA	Tampa-Hillsborough Expressway Authority
TRB	Transportation Research Board
TTC	Time to Collision
TTI	Texas Transportation Institute
UDOT	Utah Department of Transportation
USDOT	United States Department of Transportation
UTC	Utilities and Transportation Commission
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VANET(s)	Vehicular Ad-Hoc Network(s)
VDOT	Virginia Department of Transportation
WAVE	Wireless Access in Vehicular Environments
WSM	WAVE Short Messages
WSMP	WAVE Short Message Protocol
WTP	Willingness to Pay

1. INTRODUCTION

Automated vehicle (AV) and Connected vehicle (CV) technologies are rapidly maturing, but the timeline for their wider deployment is currently uncertain. These technologies are expected to bring about numerous significant societal benefits: traffic safety, improved mobility, improved road efficiency, reduced cost of congestion, reduced energy use, and reduced fuel emissions. Societal, political, technical, and economic factors will influence their paths to deployment. A significant difference between the AV and CV environments is the manner in which they will be realized. Currently AVs are predicted to take a revolutionary path while CVs are expected to take an evolutionary path to deployment. Transportation professionals and researchers anticipate that AV/CV will introduce big changes in the way Americans travel and the transportation system they use to do so (NHTSA, 2013). The nature of these changes and their resulting long-term impacts are unclear; they will most likely vary from state to state. State and local transportation agencies need to understand what this means for them and what actions they need to take now and in the next few years to prepare for the AV/CV future.

The objectives of this research are to:

1. Synthesize the existing state of practice and how other state agencies are addressing the pending transition to AV/CV environment
2. Estimate the impacts of AV/CV environment within the context of
   i. Traffic operations—impact of headway distribution and traffic signal coordination
   ii. Traffic control devices
   iii. Roadway safety in terms of intersection crashes
3. Provide a strategic roadmap for INDOT in preparing for and responding to potential issues

This research is necessary because state and local agencies tend to be risk averse in reacting to change. Their decisions must address the needs and requirements of multiple constituencies (i.e., the public, state legislators, and federal agencies), and they often face a lack of consensus among these constituent groups. Typically, state agencies are reactive to various issues given their funding constraints. However, with this study, INDOT can proactively learn about the changing landscape of the AV/CV environment and how it is likely to transform the transportation decisions in Indiana regarding traffic control devices, traffic operations, and intersection safety. This study is not intended to provide definitive answers on all transportation impacts; it is a preliminary phase in providing guidance for how INDOT should position itself in the next few years. It is one of the first initiatives by Purdue University and INDOT via the Joint Transportation Research Program (JTRP) to investigate a connected and autonomous future. A previous study under JTRP by Hubbard (2017) synthesized AV related legislation in different states across the US and developed guidelines on strategic planning for AVs from a legislative perspective. Future studies can be conducted depending on the Findings from these research projects.

1.1 Background Information

The background provides a context of the project and describes the current trends in CVs and AVs. The material is derived from several reports published in the states of Texas and Virginia—key centers of innovation in the AV/CV field.

1.1.1 Connected Vehicles (CVS)

CVs are defined as vehicles with the onboard communications capability necessary to establish a two-way data linkage between a system onboard and another system not onboard (Baxter, 2012). CV systems are comprised of hardware, software, and firmware that allow for the dynamic transfer of data. CVs can be connected to each other (V2V), connected to infrastructure and roadside sensors (V2I), and connected to other road users such as pedestrians and bicyclists (V2X). USDOT efforts have focused on standards development for V2V and V2I message sets and communication hardware, as well as providing significant seed money for initial CV application and hardware development, testing, and analysis. The primary barrier for CV technology has been the absence of private sector willingness to invest in the technologies. This is largely attributed to the lack of a viable business model: the first CVs will be more expensive and have almost no one else (or no other system) to talk to, resulting in little consumer demand.

USDOT interest in CV technology is due to its potential for vastly improved vehicle safety. Both V2V and V2I communication promise significant safety improvement (Brugeman et al., 2012). In the V2V realm, vehicles would broadcast (via DSRC frequency) a basic safety message that includes information such as vehicle speed, heading, and location that could be received by other equipped vehicles so that, cooperatively, crashes are avoided. V2V technology can be auto manufacturer devices that are integrated during vehicle production or aftermarket devices. In the V2I realm, safety is enhanced through communication to/from infrastructure. Broadcasts of signal phase and timing information (SPaT) at signalized intersections can be used for vehicle speed management to reduce the time vehicles spend idling at red lights and to improve traffic flow. USDOT has prioritized the safety benefits of CV technology, and NHTSA proposed a V2V mandate at the end of 2016 as originally planned. It is expected that NHTSA will not require transportation agencies to deploy V2I because of the investment in new or upgraded infrastructure this would entail. In a survey of expert opinion, most respondents felt that a V2V-only system is possible and valuable, but that a complementary V2I system would be necessary to maximize full public benefits of CV technology (Brugeman et al., 2012). When CV technology is in enough cars, infrastructure, and other road users, a vast network is created. Cars and people are able to give and receive data in real time, allowing road travelers to move more safely and efficiently. A complete CV system will generally include the following components (Wright et al., 2014):

- Roadside communications equipment (for DSRC or other wireless services) together with enclosures, mountings, power, and network backhaul.
- Traffic signal controller interfaces for applications that require SPaT data.
- Mapping services that provide highly detailed roadway geometries, signage, and asset locations for the various connected applications.
- Positioning services for resolving vehicle locations to high accuracy and precision.
- Data servers for collecting and processing data provided by vehicles and for distributing information, advisories, and alerts to users.

Progress in the CV arena has been largely driven by top down (federal to state and local) government research, recommendations, and guidance. Safety applications have been a key goal of CV to date, although operational improvements are an important objective. While technical issues are being addressed through industry and university-based research and development, other important issues in CV deployment are related to funding (e.g., infrastructure investment), security (e.g., cybersecurity related), and legal issues (e.g., liability or regulatory).

1.1.2 Autonomous Vehicles (AVS)

AVs are defined as vehicles in which at least some aspects of a safety-critical control function (e.g., steering, or braking) occur without direct driver input. Vehicles that provide safety warnings to drivers (forward crash warning, for example) but do not perform a control function are, in this context, not considered automated, even though the technology necessary to provide that warning involves varying degrees of automation. The adoption of AVs has the potential to greatly reduce, or nearly eliminate, automobile crashes by removing human error from the driving equation. AVs use sensors, cameras, light detection and ranging (LIDAR), global positioning systems (GPS), and other on-board technology to operate with reduced, limited, and/or no human interaction. AVs can be passenger, public transport, and freight vehicles. AVs are not necessarily fully autonomous. Autonomous vehicles are responsible for driving, solely and independently, of other systems. The Google Car, Waymo, is an example of a prototype autonomous vehicle.

The National Highway Traffic Safety Administration (NHTSA) has helped to clarify policy and technical discussions around AVs by defining levels of automation (NHTSA, 2013). The lowest level is no automation, where the driver is in full control of steering, throttle, and braking. Vehicles with Levels 1 or 2 automation are capable of managing one task, such as adaptive cruise control or lane centering. These are currently in production and marketplace deployment. At Level 3, the driver is able to temporarily turn attention away from the driving task to engage in other activities but needs to be available to retake control within a few seconds' notice. At Level 4, automated systems replace the driver completely, and the vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for the entire trip. NHTSA policy anticipates that at Level 4 the driver will provide destination or navigation input, but will not be expected to be available for control at any time during the trip, whether the vehicle is occupied or not. Level 5 automation will replace the driver for all aspects of the trip under all conditions. It represents full automation.

AVs are a complex technology that requires testing on public roads. An AV must navigate many real-world situations that cannot be effectively simulated. Public road testing of the vehicles will advance the vehicles to market. Nevertheless, there are a number of technical, economic, legal, and policy challenges that may act as barriers to the implementation and commercialization of AVs. Even though auto manufacturers are achieving higher and higher levels of automation, the production of fully driverless cars that can handle any road situation under any weather condition will require extensive research and testing. Alongside the future testing by private sector entities, the public sector will need to consider the necessary legal framework or regulation detangling for allowing self-driving autos on the road. Some states have enacted testing regulations to ensure the evaluation of self-driving automobiles does not result in harm to system users. Other states are considering legislation, while many have reviewed state legislation only to confirm that AV testing was not prohibited. States will also have some role in determining the assignment of liabilities when accidents involving driverless cars occur. At the same time, there are standards issues, such as certification, driver's licensing, cybersecurity, and fail-safe operation that will involve some public sector state agencies.

Policy challenges exist at many levels of government. Privacy issues are a growing national concern, especially as the Internet and technology have made personal information more accessible and easier to collect, access, repurpose, or manipulate. Questions regarding the security, ownership, and use of automotive telematics data must be resolved to ensure policymaker and consumer acceptance of AVs. At the state and local levels, there are issues relating to the effects on traffic control, safety, lighting and relating to road traffic regulation, including road access and rules of the road. Variations in state legislation could hinder the commercialization of AVs across the country. Many states do not have consistent definitions regarding "driver" or "operator" of the car, and so, it might take federal intervention to standardize terms and their application in the context of AVs. Currently, there is no clear direction on how state agencies should prepare themselves for this uncertain AV/CV future.

1.2 Scope of this Study

1.2.1 Part 1

Task 1 Literature Review. Conduct a comprehensive literature review on previous research and implementation of CV/AV technologies and impacts. The literature review will discuss various testbeds that states such as California, Michigan and Virginia have developed for AV/CV environments, the traffic flow data that was collected and performance measures that were developed to assess the benefit of these technologies.

Task 2 Synthesis of AV/CV Information Sources. Identify and synthesize different information sources including project reports from state DOTs and federal transportation agencies (FHWA, NHTSA), AASHTO, TRB, private companies and automobile companies about the different scenarios for AV/CV deployment. In addition, the technology impacts of AV/CV will also be documented and strategies that other DOTs are using to prepare for the AV/CV future will be reviewed. The research team will summarize how INDOT should prepare for potential scenarios of AV/CV deployment (to support the Part 1 Deliverable).

Task 3: Develop a Framework for AV/CV Impacts Assessment. The research team will develop a modeling framework for AV/CV impacts assessment. Key considerations will include the following: (1) how a mixed fleet of CV and non-CV vehicles should be modeled on a roadway segment; (2) what changes will likely take place regarding traffic control devices at intersections; (3) the state-level infrastructure that will be needed to support AV/CV deployment (e.g., roadside safety devices, pavement markings); and (4) considerations related to adapting/clarifying driving regulations (Indiana State Code) and tort liability. The modeling framework will include a set of considerations that need to be included when developing a complete model. The framework will be a flowchart of the different components that will eventually lead to the development of a set of models. No specific models will be developed in Part 2 as part of this project.

Part 1 Deliverable. A report will be submitted at the end of Part 1 of the project. Its purpose is principally to (1) advise INDOT of the state of current technology and the likely timeline of future technological advances; uncertainties in timing and technology; and recommended changes (if any) to current policy, standards, and operations (for instance, on agency position for permitting test deployments)—that is, how and when should we take action to prepare to accommodate AV/CV progression; and (2) provide further guidance in the manner and scope of Part 2 of the project. In addition, a presentation on Findings of Part 1 will be offered to the Executive Committee. Based on the outcome of Part 1, feedback from stakeholders—including the SAC and JTRP Executive Committee—the tasks in Part 2 will be potentially revised.

1.2.2 Part 2

Task 4: Develop a Framework to Evaluate the Mobility Impacts of AV/CV Environment. We will develop a modeling framework that will evaluate the congestion impacts due to AV/CV environment using the framework developed in task 3. The potential benefits in terms of overall reduction in congestion, the benefits of travel time reductions with different levels of AV/CV penetration will be modeled. The research team will use VISSIM and agent based modeling tools developed by Dr. Ukkusuri to evaluate the potential reduction in delays, increase in speeds on various corridors. Specific corridors will be tested based on the input of SAC members.

Task 5: Testing Impacts on Intersection Crashes and Signal Coordination Due to AV/CV Environment. The project will summarize the potential benefits to reducing intersection crashes due to different levels of automation in the AV/CV environment at various levels of AV/CV market penetration. Similarly, the research team will identify the changes that will potentially be needed in the context of traffic signal coordination. There have been studies, which have shown that, perhaps, there will be no need for signals anymore within an AV environment leading to autonomous intersections. The research team will document the changes that are expected in the context of signal timing, signal coordination, speed harmonization within both the AV and CV environments. Sample results based on the research studies of Dr. Ukkusuri will be presented to clearly demonstrate the necessary changes in intersection control.

Task 6: Strategic and Tactical Advice to INDOT for an AV/CV Future. Based on research done in tasks one through five, the research team will provide a set of recommendations to INDOT to allow positioning for an AV/CV future. These strategies will include decisions related to (1) the timing of various investments for operational and planning changes that INDOT should conduct; (2) the potential need for a specific individual or group of individuals within the organization to be responsible for AV/CV operations; (3) potentially establishing a working relationships with state or regional resources with useful expertise, such as universities, UTCs, and industry; (4) identifying state and local policymakers to familiarize and educate about AV/CV; and (5) establishing an internal group made up of various stakeholders to develop a strategic plan for implementation.

Project Deliverables

1. Synthesis document of AV/CV environment. The research team will develop the current state of practice in AV/CV deployment and how other state agencies are positioning themselves in the rapidly evolving area.
2. Documented framework for impact assessment. Document the modeling framework for AV/CV deployment especially in the context of traffic signal coordination, potential reductions in travel time in various corridors and changes to pavement markings. The impact assessment will provide a clear direction about potential changes for INDOT to make 5, 10, and 20 years from now. Clear and concise documentation of the project is provided to INDOT for analysis, revision, and further developments.
3. Presentation to INDOT staff. A strategic level presentation will be made to INDOT staff about the Findings and advise whether INDOT needs to make any changes in the short term to prepare for AV/CV with specific emphasis on signal intersections, safety and markings. Other issues related to regulation and financing will also be discussed in the presentation.

PART 1

2. A SYNTHESIS OF CURRENT PRACTICES AND RESEARCH RELEVANT TO AUTONOMOUS AND CONNECTED VEHICLES

2.1 Introduction

To have a better understanding of the context in which AV/CV development is occurring, an organizational chart of relevant transportation authorities and other organizations was developed (see Figure 2.1). Pilot programs for AV/CV deployment, such as those occurring in Wyoming, Tampa Bay, and New York City, are regulated by those issuing the technology, funding, and ordering these programs to occur. Predominantly, state DOTs, expressway authorities, automobile industry OEMs, and university research arms collaborate in these aspects of pilot program deployment. State DOTs are guided by their standard setting

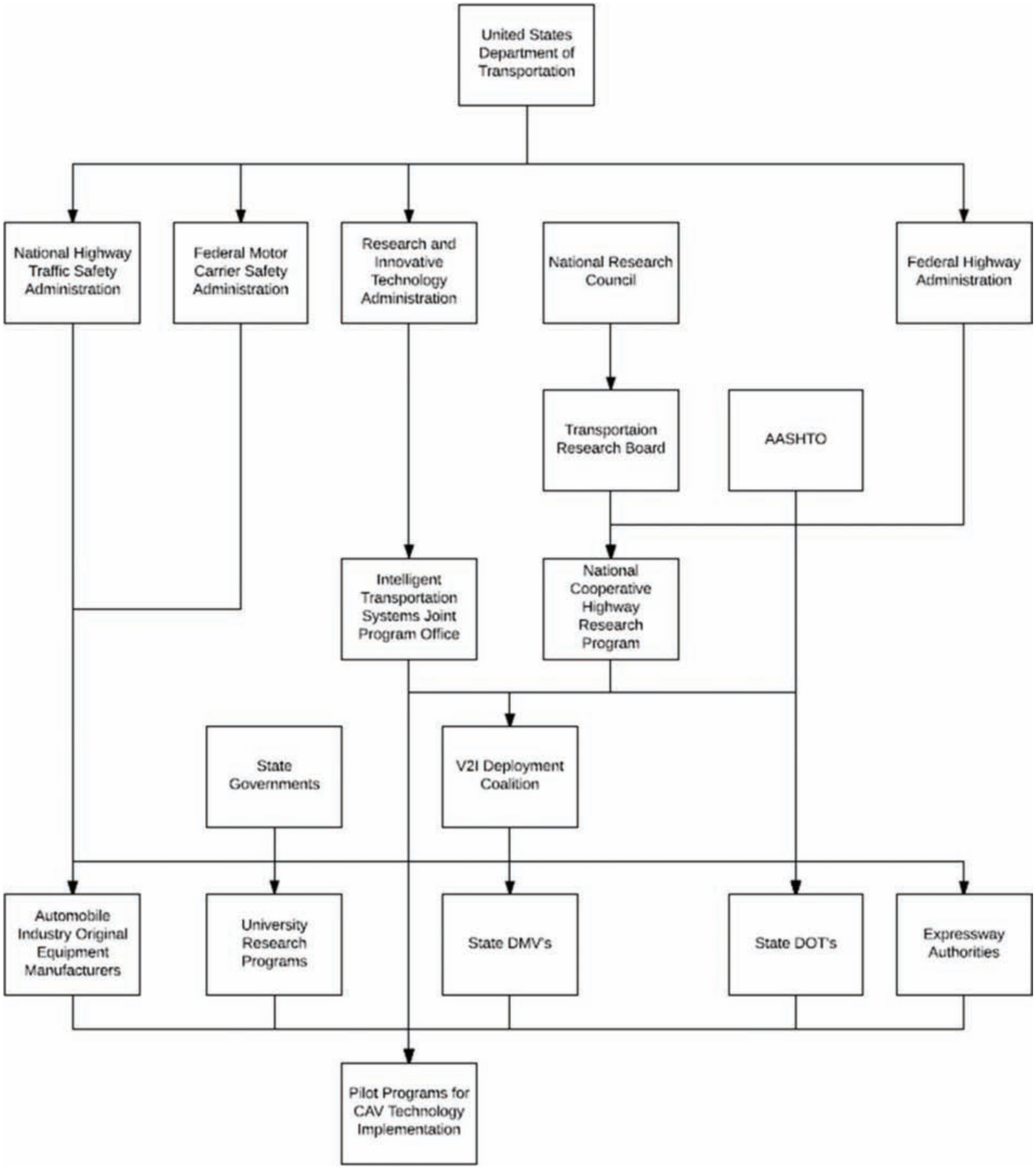


Figure 2.1 Interlinkage between various state and federal agencies in the AV/CV space.

body, AASHTO. The Federal Highway Administration provides state DOTs with funding to complete projects.

State DOTs can request research from the National Cooperative Highway Research Program (NCHRP) to address the issues they face. NCHRP is overseen by the Transportation Research Board, a division of the National Research Council. University research programs are run by state governments. Automobile industry OEMs are governed by standards set by the National Highway Traffic Safety Administration (NHTSA) and Federal Motor Carrier Safety Administration (FMCSA). The V2I deployment coalition is a standards setting group charged with ensuring interoperability in connected vehicle technology. AASHTO is a governing body of this coalition. Federal research on AV/CV technology is carried out by the Intelligent Transportation Systems Joint Program Office (ITS JPO), which is a division of the research and innovative technology administration. The NHTSA, FMCSA, Research and Innovative Technology Administration, and Federal Highway Administration are all overseen by their parent body, the United States Department of Transportation.

2.2 Technological Aspects of AVs and CVs

2.2.1 Approval Authorities

Introduction. The main source of approval for CAV technology will come from vehicles meeting standards issued by government bodies (National Conference of State Legislatures, 2017). However, from a national perspective, approval standards ensuring CAV technology's implementation are fragmented and vary on a state-by-state basis.

Autonomous Vehicles. For autonomous vehicles, where regulation is necessary to ensure that the technology utilized by consumers will enhance their safety, a national inconsistency in regulatory rulemaking is clear. Although 41 states, at a minimum, have considered legislation pertaining to autonomous vehicles in the past five years, only nineteen have passed one piece of relevant legislation (National Conference of State Legislatures, 2017). As a result, automakers face wide inconsistencies in registration requirements among states. For instance, in 2016, Uber violated California registration requirements for autonomous vehicles through failing to acquire the permits autonomous vehicles require. These permits apply exclusively to autonomous vehicles (Larson, 2017). As a result, Uber temporarily moved its testing to Arizona, a state with no special regulations for autonomous vehicles, where it could proceed with testing unhindered.

Additionally, states that have partaken in regulating autonomous vehicles are at various stages in managing the technology. For example, while both Utah and Michigan have passed legislation relating to autonomous vehicles in the past 5 years, Michigan is at the forefront in regulating the technology, while Utah is simply beginning the process of doing so (National Conference of State Legislatures, 2017). Among the many laws it has enacted, Michigan has legalized autonomous vehicles under certain conditions, clearly defined the technology, permitted its testing, and managed numerous potential liability issues. On the other hand, Utah has simply commissioned a study to evaluate appropriate safety features and regulatory strategies for managing autonomous vehicles (National Conference of State Legislatures, 2017).

During the final year of the Obama Administration, the federal government sought to address the lack of unified national safety standards for autonomous vehicle approval. The NHTSA issued guidelines in September 2016, including a 15-point safety standard for the "the design and development of autonomous vehicles" (Kang, 2016a). The government "called for states to come up with uniform policies applying to driverless cars" (Kang, 2016a). The standard includes mandates for vehicles to be secure from cyber-attacks, collect data to improve the technology after faults, and meet the NHTSA's standards for crashworthiness that apply to non-automated vehicles (Kang, 2016b). It must be stressed that the standard is included in a set of guidelines, which are not being enforced with inspections. Instead, the government was intentionally vague because it strived to "outline the areas that need to be addressed and leave the rest to the innovators" (Kang, 2016a). Nevertheless, vehicles that violate the safety standard will be recalled by the NHTSA (Kang, 2016a). The standard currently represents the extent of unifying approval regulation for automated vehicle technology.

Connected Vehicles. Similar to autonomous vehicles, regulations and standards for the approval of connected vehicles are not fully developed. The NHTSA was supposed to establish rulemaking on vehicle-to-vehicle communications in 2016 (ITS JPO, n.d.f). However, as of July 2017, the rulemaking has not been completed. Nevertheless, some agencies involved in the rulemaking have revealed several of its major components. Current rulemaking efforts are made up of contributions from the ITS JPO, NHTSA, Society of Automotive Engineers International (SAE), Institute of Electrical and Electronics Engineers (IEEE), and the Crash Avoidance Metrics Partnership (ITS JPO, n.d.f).

SAE J2735 will "assure that DSRC applications are interoperable" (ITS JPO, n.d.f). Interoperability of applications is essential to the success of CV technology, as vehicles from various manufacturers must be able to communicate to perform effectively. These applications include collision avoidance systems and emergency warnings to drivers (ITS JPO, n.d.f). In order to support this interoperability, J2735 mandates a data dictionary, consisting of 16 essential messages to be delivered by all CVs. These messages include an intersection collision avoidance message, road side alert message, emergency vehicle alert message, and personal safety message. To further ensure these messages are deliverable across all CVs, J2735 establishes 156 fundamental data frames and 231 essential data elements (Misener, 2016). In addition, SAE J2945 establishes performance requirements and necessary safety features to maintain a high standard of V2V performance (ITS JPO, n.d.f). Requirements include the minimum criteria for a basis safety message transmission, which must contain a variety of information such as the time, message count, a randomized ID number, the vehicle's position, and details of the car's physical state (speed, heading, and acceleration) (Misener, 2016). Furthermore, SAE J2945 lays the groundwork for a potential DSRC mandate through enabling an "always on" transmission of safety messages. It goes further and specifies that a second DSRC radio is required for multi-channel operation (Misener, 2016).

The previously outlined SAE standards for connected vehicles represent a small portion of the upcoming NHTSA collaborative rulemaking on V2V communications. Once published, this rulemaking will represent the most comprehensive set of standards to-date for the approval of future connected vehicles.

2.2.2 AV/CV Applications

Context of Applications. Presently, America's infrastructure is crippled by inefficiencies and faults. Several statistics indicate the magnitude of these problems. According to the National Highway Traffic Safety Administration (NHTSA), in 2013 alone, there were 5.6 million crashes, which resulted in 32,719 deaths (ITS JPO, n.d.e). Furthermore, per the Texas Transportation Institute (TTI), approximately 6.9 billion hours were wasted in traffic by US highway users in 2014. These inefficiencies had a negative environmental impact, as TTI estimates over 3.1 gallons of fuel were wasted by traffic and other instances of poor usage in 2014 (ITS JPO, n.d.e). The numerous potential applications of both automated and connected vehicles have the potential to rectify many of these issues.

CV Applications Overview. The key applications of connected vehicles can be categorized by their nature: vehicle to infrastructure (V2I) safety applications, vehicle-to-vehicle (V2V) safety applications, environmental applications, mobility applications, and road weather applications. In their totality, these applications are projected to be enormously beneficial on society. As estimated by a 2015 Intelligent Transportation Society of America study, CV applications alone can result in up to $178.8 billion in benefits if deployed to levels of complete saturation across all US vehicles (ITS JPO, n.d.e).

CV V2I Safety Applications. The various types of V2I safety applications are projected to yield significant dividends if proper saturation levels are achieved. These applications consist of the vehicle interacting with its environment, such as technology in intersections used to improve driver situational awareness. USDOT estimated the safety benefits of some of these applications through assessing the results of multiple CV application deployment efforts and studies (ITS JPO, n.d.e). It must be noted that the estimated safety benefit figures represent CV technology performing at its maximum potential and may not be fully realized.

- Pedestrian in signalized crosswalk warnings alert transit bus operators of pedestrians in crosswalks ahead of the bus, reducing pedestrian-vehicle conflicts by up to 50% per FHWA (Arnold & Walker, n.d.).
- Red light violation warnings broadcast "signal phase and timing (SPaT) and other data to the in-vehicle device," which enables the driver to be warned of red light violations (ITS JPO, n.d.c).
    - Coupled together, these two warning systems are projected by USDOT to eliminate up to 250,000 crashes and save 2,000 lives per year (ITS JPO, n.d.e).
- Curve speed warning systems provide alerts to drivers approaching curves at dangerously high speeds. According to USDOT, these can prevent over 169,000 crashes and save 5,000 lives (ITS JPO, n.d.e).
- Stop sign gap assist message systems warn drivers of potential collisions at stop sign intersections (ITS JPO, n.d.c). These are supposed to reduce congestion from incidents by 30%, as calculated by FHWA (Arnold & Walker, n.d.).
- Reduced speed/work zone warnings employ roadside equipment to inform drivers of necessary maneuvers when approaching work zones (ITS JPO, n.d.c). This will improve the efficiency of work zone travel, increasing travel time reliability by up to 30% per FHWA (Arnold & Walker, n.d.).

CV V2V Safety Applications. In addition to V2I safety applications, V2V safety applications are also projected to improve the safety of motorists. In contrast to V2I safety applications, V2V safety applications consist of the vehicle interacting with other vehicles. However, the result of these applications is the same: improved driver awareness.

- Emergency electronic brake lights are designed to improve driver awareness of stoppages in traffic through alerting them of hard braking ahead of them, giving drivers more time to evaluate the situation (ITS JPO, n.d.d).
- Forward collision warning (FCW) systems perform a similar purpose to that of emergency electronic brake lights. However, instead of warning of developments in distant traffic, FCW systems deliver alerts of imminent collisions ahead.
- Intersection movement assist (IMA) applications warn the driver when entering an intersection is unsafe. An example of an unsafe scenario is when cars are moving through the intersection, but are not visible to a turning vehicle.
- One technology already being implemented is blind spot/lane change warning (BSW/LCW) systems, which alert the driver if vehicles are in adjacent lanes that the driver is turning into. This will serve to prevent unsafe lane changes.

- Based on a numerical assessment of the crashes occurring in their areas of application, IMA, FCW, and BSW/LCW V2V safety features are projected by the NHTSA to prevent up to 45,775 crashes annually, with the potential to save 857 lives (Chang, 2016).
    - Of these crashes, IMA will be the most effective, preventing 50% of the total.
    - Because of these crash preventions, up to $7,848 million will be saved, per the NHTSA (Chang, 2016).

- Left turn assist warnings serve to facilitate safe left turns across the opposing lane of traffic. To avoid head on collisions, alerts are delivered to the driver if undetected vehicles are in the opposing lane when the turn is attempted. The previous applications are applicable to all vehicle types.
- A V2V safety application specific to transit vehicles is the vehicle turning right in front bus warning. This application will alert transit bus operators if vehicles are moving them as the bus departs a bus stop (ITS JPO, n.d.d).

CV Environmental Applications. Several connected vehicle applications are intended to benefit the environment through saving fuel and lowering emissions.

- A V2I application, eco-approach and departure at signalized intersections facilitates the prevention of vehicle stoppages due to red lights (ITS JPO, n.d.a). The current state of the signal and time remaining is broadcast by technology at the intersection to approaching vehicles. As a result, the vehicles can optimize their speeds and avoid stopping at intersections (ITS JPO, n.d.a). Vehicles release more emissions after stopping at intersections when compared instances where stopping did not occur. Furthermore, vehicles waste time stopping at intersections because smooth flow is disrupted.
    - Eco-approach and departure at signalized intersections technology is approximated by FHWA to rectify these problems through reducing vehicle emissions by 20% and improving travel times by 10% (Arnold & Walker, n.d.). The technology is beneficial and flexible, for it can be optimized for improving mobility or the environment, depending on a transportation authority's needs (Arnold & Walker, n.d.).
- Eco-traffic signal timing, employs data collected wirelessly from vehicles to optimize the traffic signal performance depending on demands, which will yield reductions in fuel consumption and emissions (ITS JPO, n.d.a).
- Eco-traffic signal priority technology gives transit or freight vehicles the ability to request signal priority when approaching intersections. Whether this request is granted depends on computations performed automatically at the intersection, which will determine whether granting priority is environmentally beneficial given vehicle type, passenger count, and the vehicle's schedule.
    - Together, Eco-traffic signal timing and signal priority are projected by USDOT to reduce carbon dioxide emissions and fuel consumption by approximately 11% (ITS JPO, n.d.e).
- Freeway lane management applications that are optimized for the environment, such as dedicated eco lanes and speed limits that are determined with an environmental focus, can yield fuel savings of up to 22% for the vehicles utilizing these applications.

CV Mobility Applications. Connected vehicle technology can be employed to facilitate improved vehicle mobility, reducing congestion and improving the productivity of infrastructure systems. At intersections, mobility benefits are extracted through installing an intelligent traffic signal system (ITS JPO, n.d.b). This accommodates a variety of signal control applications.

- Transit signal priority and freight signal priority applications provide signal priority to transit and freight at intersections, allowing them to avoid stopping at intersections (ITS JPO, n.d.b). These signal priority systems yield benefits for vehicles employing them, reducing their travel time by up to 27% (ITS JPO, n.d.e).
- Dynamic speed harmonization systems "recommend target speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes" (ITS JPO, n.d.b). This improves the efficiency of travel for vehicles employing them.
- Cooperative adaptive cruise control (CACC) applications adjust cruise control speeds in coordination with other vehicles, enabling platooning. CACC yields dividends through improving traffic low.
    - Together, CACC and dynamic speed harmonization have the potential to reduce traffic. USDOT estimates these technologies can reduce travel time by up to 42% if implemented to levels of full saturation (ITS JPO, n.d.e).
- Mobility applications can save lives when emergency vehicles are emphasized (ITS JPO, n.d.b). Emergency vehicle preemption gives signal preemption to emergency vehicles, enabling them to better traverse traffic in congested areas and reach their destination in less time.
- Mobile accessible pedestrian signal systems allow visually impaired pedestrians to call traffic signals with their smartphones. These systems are especially effective when the visually impaired individual is unable to locate push buttons effectively. When the signal is called, audio cues through smartphones give pedestrians coordination of when to navigate the crosswalk as well (ITS JPO, n.d.b).

CV Road Weather Applications. The last key connected vehicle application, road weather applications, enable a significant amount of data to be gathered that can be employed to "assess, forecast, and address the impacts that weather has on roads, vehicles, and travelers" (Hill, 2013). This data will improve the management of road-weather response on roadways.

- Enhanced Maintenance Decision Support System (MDSS) applications enable road weather data to be collected from connected vehicles. Vehicles to be equipped with MDSS include snowplows, government vehicles, and vehicles used by the general public. The amount of detailed data generated by MDSS will enhance road treatment plans and develop recommendations on driving behaviors in various weather conditions.

- Weather-Responsive Traffic Management systems can improve road safety through coordinating the operation of variable speed limits and intelligent traffic signal systems depending on weather conditions.
- As far as variable speed limits are concerned, information gathered from connected vehicles can be employed in algorithms to refine posted speed limits and maximize traffic safety. At intersections, data collected from connected vehicles will be utilized to "select special signal timing plans that are most appropriate for the prevailing conditions" (Hill, 2013).

AV Applications Overview. In addition to connected vehicles, autonomous vehicle technology has numerous assets that can be leveraged to yield a variety of infrastructure benefits. Autonomous vehicles integrate many features similar to those that can be found on connected vehicles, such as connected adaptive cruise control and forward collision warning. However, autonomous vehicles employ these features through means that lower driver responsibility. At higher levels of automation, such as Levels 4 and 5, driver control is extremely limited. In contrast, the lower levels consist of isolated instances of automation—one key process is managed, while driver control is required in all others. The benefits of autonomous vehicle technology are most evident in enhancing traffic safety. Key autonomous vehicle applications that improve traffic safety are adaptive cruise control (ACC), lane keeping assistance, lane centering, automatic emergency braking, parking assistance, and traffic sign recognition.

Adaptive Cruise Control. When activated, ACC allows the car to automatically adjust its speed to avoid colliding with traffic ahead of it through employing frontal sensors and cameras (Mehler, Reimer, Lavalliere, Dobres, & Coughlin, 2014). ACC is seen as "A technology that was developed largely as a convenience feature that has been considered as offering some modest potential safety benefit under limited circumstances" (Mehler et al., 2014). As a result of its convenience emphasis, ACC's safety applications do not have a significant impact on the safety of motorists overall. A 1999 NHTSA test estimated that ACC employed at saturated levels would reduce rear end collisions by 13,000 in 1996. This constituted less than 1% of all crashes at the time. Nevertheless, at higher levels of autonomy, ACC can be combined with other technologies, such forward collision warning systems and autobrake features, to generate safety improvements of much greater magnitude (Mehler et al., 2014).

Lane Keeping Assistance and Lane Centering. Lane keeping assistance and lane centering are two similar autonomous technologies with a key distinction. Both applications employ windshield-mounted cameras to alert drivers when they drift too close to the edges of the lane they occupy and perform counteracting measures (Howard, 2017). Lane keeping assist technology confines the vehicle to the lane it occupies unless directed to leave. When it begins to drift outside the lane, the vehicle automatically steers itself away from the lane marking. Lane keeping assist does not center the vehicle; the driver must do this. On the other hand, lane-centering technology automatically centers the vehicle in its current lane. The application will be activated as long as hands are in contact with the steering wheel. Both of the aforementioned lane guidance technologies are easy to overcome with minimal steering effort, meaning normal driving behaviors can be seamlessly executed even with the lane technologies installed (Howard, 2017).

Automatic Emergency Braking. Automatic emergency braking applications are intended to reduce the prevalence of rear end collisions on roadways, which are commonly attributed to poor driver awareness (NHTSA, n.d.). The collisions are a significant problem, constituting one third of all police-reported crashes in 2012. To prevent these, automatic emergency braking systems detect imminent forward crashes and perform a counteracting measure contingent on the technology being employed. If the system employed is dynamic brake support technology, the driver must initiate braking. When braking is being executed, if more input is needed to prevent a collision, the dynamic brake support technology will automatically add this. If the system employed is crash imminent braking technology, no braking needs to be initiated. The vehicle's brakes will be applied automatically (NHTSA, n.d.).

Parking Assistance. Parking assistance technology allows for the difficult process of parallel parking to be partially automated (Healey & Mays, 2012). The driver is required to locate an available spot and position the vehicle alongside it. Parking assistance will steer the vehicle. However, it is required that the driver operate the accelerator and transmission, switching it to either forward or reverse depending on the circumstances. 360-degree cameras are employed to improve situational awareness during the parking process. This automated application is already being introduced into consumer markets by several major automakers, including Ford, Audi, BMW, and Toyota (Healey & Mays, 2012).

Traffic Sign Recognition. Traffic sign recognition is designed to enhance driver and pedestrian safety through notifying the driver of speed limits, road works, pedestrian crossings, and other hazards in the vehicle vicinity (Karthiga, Mansoor Roomi, & Kowsalya, 2016). As a result, the driver will have improved awareness of what is in the vehicle's environment and be able to adjust his or her behavior accordingly. The technology is able to identify signs through employing visual recognition features collected through peripheral cameras. A sign's visual features are matched with various images in a database containing hundreds of sample signs. The most similar database image is subsequently identified as the sign encountered. If a sign is not in the database, there is a strong possibility that it will not be properly read. This will occur for non-standard signs.

After identification, the driver is alerted through the sign being displayed on an information panel. While traffic sign recognition technology has potential to dramatically enhance driver environmental awareness, it is currently unreliable. A recent study by TCE Madurai measured traffic sign recognition's classification accuracy to be 63% (Karthiga, Mansoor Roomi, & Kowsalya, 2016). A common instance in which defects occurred is when more than one sign was in the vehicle's periphery. This fault and several others must be rectified before traffic sign recognition can be introduced into consumer markets.

2.2.3 Manufacturers' Standards (DSRC)

Introduction to Standards. Dedicated short-range communications (DSRC) technology is the predominant form of communications for connected vehicles. Although other technologies are advocated, most government and industry standards for V2V and V2I on-board equipment (OBE) and roadside equipment (RSE) are specifically focused on DSRC. This is because significant investments have been made in DSRC by the federal government. Besides monetary investments, the Federal Communications Commission (FCC) has allocated 75 MHz of spectrum from 5.85 to 5.925 GHz for DSRC operation in the US (Kenney, 2011). Furthermore, impending rulemaking will potentially mandate the installation of DSRC in all new vehicles starting around 2022 (Bayless et al., 2016).

Evolution of DSRC. DSRC is an evolving technology, as evidenced by the dramatic improvement in its performance that occurred during the 2000's (Weigle, 2008). DSRC was transformed from its previous variant, to a much more sophisticated, applicable version. The old variant had a frequency of 915 MHz, range of less than 30 meters, data transfer rate of .5 Mb/s and did not feature V2V communication capabilities. These performance figures reflect the nature of the technology, as it was designed primarily for electronic toll collection. In contrast, the current DSRC technology has a frequency of 5.9 GHz, range of up to 1000 meters, data transfer rate of 27 Mb/s, and can be employed for both V2V and V2I communication purposes (Weigle, 2008).

Context of Standards. The rapidly evolving nature of DSRC technology warrants manufacturer standards to guide OBE and RSE equipment manufacturers in ensuring the interoperability, efficiency, and security of DSRC systems. Several standards established by the Institute of Electrical and Electronics Engineers (IEEE), in close coordination with the government, are intended to achieve the interoperability, efficiency, and security of DSRC systems (Kenney, 2011). The following standards are prime examples of those that have been developed by the IEEE or other organizations. These will eventually form a portion of a comprehensive set of standards for DSRC technology, which has not yet been developed. It must also be noted that all standards are applied to OBE and RSE equipment.

IEEE 802.11: Communication Performance Requirements. IEEE 802.11 defines communication performance requirements for DSRC receivers and transmitters (Kenney, 2011). Three channel widths can be employed by DSRC technology: 5, 10, and 20 MHz DSRC transmitters will most commonly employ the 10 MHz channel. This channel must support data transfer rates of 3, 6, and 12 Mb/s. In higher vehicle density environments, higher transfer rates may be applicable as well. DSRC transmission receptors must support the 5, 10, and 20MHz transmitters and their data transfer rates. Minimum sensitivity requirements for receptors have been outlined for each data rate. This is defined as the signal energy for which a 1000-byte packet will be correctly received at least 90% of the time (Kenney, 2011).

IEEE 1609.2: Security Services. IEEE 1609.2 is intended for security services and ensuring data privacy (Kenney, 2011). It accomplishes this through defining standard mechanisms for authenticating and encrypting messages. Authenticated messages must carry a digital signature that can be used to verify the sender is authorized to send the message and that the message is not altered. These messages are signed with keys sent by authorized devices. A digital certificate is contained in the DSRC device that is associated with the signing key. This serves as a mechanism to ensure the key is authentic upon reception, differentiating messages sent by authorized and unauthorized sources. For additional privacy, each vehicle must only use a certificate for a defined time period, typically 5 to 10 minutes. Certificates are discarded and generated at the end of this interval. Because of these varying certificates, it will be more difficult to track a vehicle's movements by its broadcasts. When a vehicle changes certificates, it also changes other identifiers, such as its source MAC address and temporary ID, further reinforcing privacy and security. Only one certificate will be valid at any given time, preventing the attacker from gaining access to past valid certificates and impersonating the certificate owner for personal gain (Kenney, 2011).

IEEE 1609.3: Standardized Information Sending. IEEE 1609.3 standardizes information sending (network services) so DSRC channel congestion can be averted (Kenney, 2011). Minimum characteristics for single V2V or V2I transmission, also known as one-hop transmissions and Wireless Access in Vehicular Environments (WAVE) Short Messages (WSMs) are defined in the WAVE Short Message Protocol (WSMP). All WSMs must be at least 5 bytes. Furthermore, to preserve spectrum space, prevent congestion, and ensure ease of processing, WSMs should rarely exceed 20 bytes.

Moreover, IEEE 1609.3 stipulates requirements for message contents. Each WSM should contain the current 4-bit WSMP version number. This version number will be associated with the 1609.3 standard's version at the time of WSM's sending. The provider service identifier (PSID) should be included as well. PSID's define the purpose of the message and are written in variable length format for ease of organization and bandwidth efficiency. Optional aspects of WSMs can be included in extension fields. If optional information is included, it must be labeled with the channel number of use, data rate being employed, and transmission power used. Every WSM must end with the WSMP WAVE Element ID, which is a one-byte field that marks the end of all extension fields and indicates the format of the WSM data field (Kenney, 2011).

IEEE 1609.4: Facilitating Connections between DSRC Devices. IEEE 1609.4 is intended to define a mechanism by which DSRC devices that are switching among multiple channels will find each other through tuning to the same channel at the same time (Kenney, 2011). This standard is applicable when DSRC is in the 5.9 GHz spectrum or operating in a multi-channel environment. IEEE 1609.4 enables easy switching between channels through designating a channel as a "special rendezvous channel that the devices will tune to on a regular basis" (Kenney, 2011). This channel is known as the control channel (CCH). All other channels in the band plan are termed designated service channels (SCH). DSRC receptor systems must alternate between 50 ms intervals, CCH followed by SCH. A 4 ms guard interval is at the beginning of each period to ensure the previous phase does not carry over. During CCH intervals, devices wishing to connect to each other will switch to CCH and rendezvous. Devices connect to each other through a vehicular or infrastructure DSRC device detecting another in the vicinity. If a particular application is requested by the automated infrastructure system, for example the red light warning systems or the vehicle, connection will be initiated. DSRC radios do not have to switch to the CCH interval during the time period. This exclusivity allows devices that want to switch to be exclusively on the CCH interval, reducing interference from other DSRC devices (Kenney, 2011).

2.2.4 Current Tech Legislation (DSRC)

NHTSA Justification for Current Rulemaking. With the development of DSRC and associated standards, the NHTSA has advocated the institution of rulemaking to rapidly increase the institution of DSRC technology into new vehicles. In 2014, the NHTSA began suggesting that a V2V standard should be required by the automobile agency for new manufactured vehicles (Bayless et al., 2016). The mandate would require all new vehicles to have DSRC technology. Consequently, all new vehicles would be connected vehicles. In a statement issued, the NHTSA justified this development through making it clear they are convinced "the DSRC radio platform and communications standards will foster innovative and competitive safety applications development" (Bayless et al., 2016). This development would occur among original equipment manufacturers (OEMs) and consumer electronics hardware providers. The technology industry reacted favorably to this development, as one executive at a major semiconductor manufacturer observed "if V2V gets mandated, regardless of technology, it will only help perpetuate the whole idea of the intelligent, situationally aware vehicle" (Bayless et al., 2016).

Process of NHTSA Rulemaking and Initial Impact. The NHTSA's proposed rulemaking came closer to fruition on December 13, 2016, when the NHTSA published the notice of proposed rulemaking (NPRM) for what will mandate DSRC installation in new vehicles (Abuelsamid, 2016). The actual date of the rule's institution is unclear. However, it is estimated that the process will take approximately a year to complete. After the rule is made, it will be introduced within several years and have an immediate impact. According to NHTSA Representative Bryan Thomas, two years after the rule is made, "the phase in period begins with half of new vehicles in the first year being affected, 75% in the second year, and 100% from the third year on" (Abuelsamid, 2016). With 100% of new vehicles requiring the installation of DSRC systems five years after the rule is made, it is clear that the new rulemaking will result in significant market penetration of CVs.

USDOT Interviews on Rulemaking. A 2016 USDOT study assessed the potential impact of the NHTSA's proposed DSRC mandate and gathered opinions from figures in government and industry (Bayless et al., 2016). Regulations such as the proposed rulemaking are required to initiate any CV market penetration, as a lack of regulations is currently causing uncertainty that is hindering the technology's advancement into consumer markets. As an interviewed chief strategy officer of a tier one supplier remarked, "A hindrance to V2X would be no regulatory movement whatsoever" (Bayless et al., 2016). In fact, among the numerous figures in government and industry interviewed by USDOT, there was complete consensus that rulemaking is needed to drive DSRC development, adoption, and accelerate market penetration.

USDOT Projections for NHTSA Rulemaking's Impact. The study concluded that, not only will the mandate increase market penetration of DSRC technology through the device's installation on new vehicles, but it will also increase the prevalence of DSRC technology on existing vehicles through consumer adoption (Bayless, et al., 2016). USDOT projects the appearance of mandated DSRC equipment in large numbers will prompt consumers to purchase the relatively inexpensive systems for their existing vehicles. This will begin when 30% of vehicles have DSRC radio installed in them, estimated by USDOT to be 2026 if the rulemaking comes into full effect in 2022. Just two years later, consumer installations will outpace that of automotive OEMs. Three years later consumer installations will be occurring at double the rate of those in factories. By 2030, 70% of all vehicles are projected by USDOT to have DSRC (Bayless et al., 2016). Although the technology has a cost, it is relatively inexpensive. Hence, adoption by consumers will occur if market penetration is increased by a federal mandate (Bayless et al., 2016).

An Alternative to DSRC: 5G. While rulemaking is currently in the process of being instituted to mandate DSRC, proponents of a competing technology, 5G, are challenging the legitimacy of such a requirement. The FCC wants to reserve space for 5G in the 5.9 GHz spectrum to perform vehicle safety functions, similar to those performed by DSRC, while also serving an entertainment purpose through expanding internet access (Alleven, 2016). It must be noted that the FCC currently has regulations on DSRC technology, specifying licensing and service rules. 5G is "still very much in the draft stages" (Nordrum, 2016). Standards defining details even as simple as what the term "5G" means are being drafted (Nordrum, 2016). Despite lack of current development, 5G will eventually be able to "compete with DSRC in terms of latency, security and guaranteed throughput," per Dominique Bonte, an ABI Research vice president (Bradbury, 2016). The key advantage of 5G technology over DSRC is that it will run off existing infrastructure: current wireless networks. Upgrades in 5G technology will still need to be made at cellular stations, but the infrastructure is present to support those. On the other hand, DSRC's adoption will require taxpayers to fund a national introduction of DSRC roadside stations. 5G can also be used for entertainment purposes, which will enable it to be a unifying connectivity technology for cars through integrating safety and entertainment features (Bradbury, 2016). However, given DSRC's established nature, it should be INDOT's primary area of work in the present and future. INDOT should stay informed with 5G developments, but DSRC should be the agency's focus for CV infrastructure.

2.3 Changes in Traffic Control Devices for AV/CV

Overview. With the advent of automated and connected vehicles, traffic control device technology will change dramatically. At signalized intersections, DSRC hardware and software systems must be installed to facilitate the implementation of connected vehicle technology at intersections. This installation will occur as a part of the institution of Multi-Modal Intelligent Traffic Safety Systems (MMITSS), which are "the next generation of traffic signal systems" (ITS JPO, n.d.i). As a result of the installation of DSRC technology through MMITSS, numerous benefits will be seen at intersections. These include intelligent traffic signal control, signal priority, and pedestrian signal systems accessible via mobile device.

DSRC Hardware Installation. Before any DSRC software is implemented to enable CV applications to function, DSRC hardware must be installed at intersections. This installation process is being conducted by state DOTs on a nationwide basis in order to fulfill the SPaT Challenge (Leonard, B. D., 2017). The primary hardware component necessary for DSRC operation at intersections is the DSRC roadside unit. The roadside units contain the radio system, which is responsible for sending and receiving messages (Leonard, B. D., 2017). Each DSRC roadside unit follows a 5.85-5.925 GHz radio spectrum, which was granted by the FCC. This consists of seven 10-MHz channels and one 5-MHz channel (Leonard, B. D., 2017). These channels allow for the organization of communication according to their purpose. For example, channels 172 and 184 are designated for safety of life and property (Leonard B. D., 2017). Channel 182 is the priority channel. Unlike onboard DSRC units, roadside unit standards have been published for manufacturers to design to. These standards include security requirements, mandate single and dual channel alternating DSRC, and require the presence of internal computer processing and permanent storage systems (Leonard, B. D., 2017).

Along with the roadside units, several other pieces of hardware are required at intersections. These include roadside processers and signal controllers (Leonard, B. D., 2017). The processer will evaluate the message received from a car's onboard DSRC equipment and determine the appropriate application. Depending on the application, signal phase and timing (SPaT) or intersection map (MAP) data will be requested by the processor. This processor could be in the DSRC system, in the signal controller, or a standalone piece of hardware (Leonard, B. D., 2017). Signal controllers are employed to enable applications requiring SPaT data. A command will be sent to them from roadside processors requesting SPaT data, then the data will be outputted (Leonard, B. D., 2017). Along with these fundamental hardware components, other significant hardware costs will be accrued in MMITSS installation (Office of the Assistant Secretary for Research and Technology, 2014). Communication connection equipment, power connection equipment, and additional installation equipment, depending on the intersection, will cost thousands of dollars per DSRC site. Across several states, the average total DSRC hardware cost was reported at $7,450 per intersection (Office of the Assistant Secretary for Research and Technology, 2014).

DSRC Software Installation. From a software standpoint, message handlers are required to enable DSRC hardware to carry out its functions. Each MMITSS must be able to receive SPaT and MAP data from a wide range of CVs manufactured by various automakers (Leonard, B. D., 2017). These messages are all in accordance with the same SAE J2735 standard (ITS JPO, n.d.i). MMITSS systems cannot all be kept up to date with the latest hardware developments. Hence, software is required to enable the communication between CVs and MMITSS systems manufactured to different protocols over time (Leonard, B. D., 2017). An open source application sponsored by the FHWA, V2I hub provides a means to ensure connected vehicles can communicate with a variety of infrastructure systems, in addition to communication with MMITSS. These include traffic signal controllers, transportation management centers, pedestrian and vehicle detection systems, road weather sensors, and dynamic message signs.

Because of its capabilities, state DOTs, such as UDOT, are adopting V2I Hub in their MMITSS intersections (Leonard, B. D., 2017). V2I Hub has a SPaT plugin that communicates with a traffic signal controller. It also has a MAP plugin that produces intersection geometry. Both messages are in accordance with the J2735 standard, ensuring their compatibility. MAP data is formatted as an ASCII text file containing intersection map data necessary for MMITSS operation (Leonard, B. D., 2017). The text file has intersection information such as the identification number, coordinates, number of approaches, type of approach, and number of traffic lanes in each approach. This software works with a wide range of signal controllers. Other software systems are required to manage aspects of V2I communications with MMITSS systems (Leonard, B. D., 2017). For example, Security Credential Management Software Systems designed to ensure data privacy are being built for CV Pilot Projects. These are estimated to be available commercially by the summer of 2018 (Leonard, B. D., 2017). Furthermore, since the MAP text file contained in V2I Hub has accuracy of up to .5m, more accuracy may be required for certain CV applications. GPS Correction Factor Software will provide higher GPS coordinate accuracy for these coordinates.

Applications of DSRC Hardware and Software at Intersections. Because of the installation of DSRC hardware and the subsequent implementation of required software, a variety of MMITSS applications can be implemented at intersections. Intelligent Traffic Signal Systems will leverage data collected through V2V and V2I communications as well as pedestrian data to optimize flows in real time (ITS JPO, n.d.i). Transit Signal Priority will enable transportation authorities to manage bus services by granting buses priority at intersections. Whether a bus is granted priority or not will depend on a number of factors, such as the passenger count, whether the bus is on schedule, and the service type (ITS JPO, n.d.i). Mobile Accessible Pedestrian Signal Systems will allow visually or physically impaired pedestrians to interact with crossings and inform them of whether they are becoming unaligned with crosswalks. Similarly to Transit Signal Priority, Emergency Vehicle Preemption will open intersections to the flow of emergency vehicles. This will ensure a response reaches the location of interest as soon as possible. Lastly, Freight Signal Priority systems will provide signal priority to intersections in proximity to freight facilities (ITS JPO, n.d.i). This is intended to increase reliability and optimize costs through reducing delays in freight transportation.

2.4 AV/CV Standards Recommendations

Introduction. The national landscape of standards for AV/CVs is inconsistent and ambiguous. Standards vary to a significant degree between states. INDOT should assemble a list of consistent, concise standards for AV/CV manufacturers to meet in Indiana. In doing so, INDOT would encourage AV/CV OEMs to innovate and test vehicles within the state of Indiana before national standardization occurs. For its standards, INDOT should aggressively standardize aspects of CV technology that are a certainty to be an integral part of CVs in the future. When CVs inevitably evolve, rendering INDOT's previously made standards obsolete, the agency is strongly encouraged to adapt its standards for the changing CV landscape. The same is true for AVs. However, INDOT should not make standards based on potential aspects of AV/CV technology. With the field's fast-changing rate of growth and development, it would be foolish to make assumptions. A recommended foundation of standards for INDOT is outlined below.

Connected Vehicles. Several standards outlined by the Society of Automotive Engineers (SAE) are necessary for CV integration into the broader infrastructure system. SAE J2735 will "assure that DSRC applications are interoperable (ITS JPO, n.d.f). Without being interoperable, the DSRC systems of various OEMs will not function at saturation levels required to be effective. J2735 counteracts this by establishing a data dictionary, consisting of 16 essential messages to be delivered by every CV type, such as an intersection collision avoidance message, roadside alert message, and personal safety message. These messages are mandated to be deliverable with 156 fundamental data frames and 231 essential data elements (Misener, 2016). INDOT should model a set of standards after J2735, because, at a minimum, it will establish a functional level of CV interoperability in Indiana.

SAE J2945 will establish necessary performance requirements and safety standards, ensuring a high standard of CV performance is maintained. For instance, the minimum information to be contained in a basic safety message information is outlined, including the time, vehicle's position, and details of the car's speed, heading, and acceleration (ITS JPO, n.d.f). J2945 will encourage a potential DSRC mandate through approving of an "always on" transmission of safety messages. Instituting J2945 in support of a pending federal mandate of DSRC technology is therefore in INDOT's best interest.

Furthermore, the Institute of Electrical Engineers has developed a set of wireless communication standards, IEEE 1609.0 and 802.11. These standards support the establishment of local wireless networks with radio architecture that is focused on a single 5.9 GHZ radio interface, DSRC, instead of the various network stacks proposed by European Officials (Hong et al., 2016). Having multiple CV communications platforms will be an issue for the interoperability of all messages, including those of fundamental nature such as the basic safety message. IEEE 802.11 sets specifications for implementing DSRC local area networks and supporting vehicular communications on these networks. IEEE 1609 addresses the privacy, administration, and security aspects of these networks. Given the imperative nature of interoperability in wireless communications, at a minimum, INDOT should consider developing its standards for wireless networks to meet the requirements set by IEEE 1609.0 and 802.11.

Autonomous Vehicles. As far as autonomous vehicles are concerned, several recommendations for standards can be made. Although INDOT will have little authority to standardize autonomous vehicles, it remains pertinent for the agency to be aware of the direction in which the industry is heading. The Obama Administration proposed a 15-point safety standard for autonomous vehicles in 2015 (Kang, 2016a). The standard mandates that vehicles be secure from cyber-attacks, as cyber security is a major issue with AVs. It is imperative that AVs be immune to hackers who could potentially assume control of the vehicle and compromise public safety (Kang, 2016a). For data privacy reasons, security from cyber-attacks is imperative as well. In addition, AVs are mandated to collect data to analyze vehicle failures (Kang, 2016a). Unfortunately, technology will not be flawless upon introduction. Accidents are probable. Analyzing the cause of these accidents and fixing flaws will improve AV technology and enhance public safety in the future (Kang, 2016a). Lastly, AVs should meet crashworthiness standards set by the NHTSA for non-automated vehicles. There is no reason for AVs to be held to lower standards than SAE Level 0. INDOT must be aware that rulemaking pertaining to accidents caused by autonomous vehicles is still to be determined. There is a question as to who is at fault during such an accident. INDOT should prepare for this and other potential liability issues related to AVs.

2.5 Long-Term Infrastructure Considerations

Overview. From a long-term perspective, numerous suggestions can be firmly made to INDOT regarding infrastructure considerations. These can be categorized into several distinct areas: incorporating AV/CV technology into infrastructure systems, integrating CAV technology into daily agency operations, and identifying long-term funding options to expand the development of DSRC technology across Indiana. Each of these considerations can be achieved with measurable results in the long term, making them highly recommended for INDOT to modernize its road systems in the AV/CV era.

Incorporating AV/CV Technology into Infrastructure Systems. As far as incorporating AV/CV technology is concerned, INDOT should prioritize several applications, the deployment of which can be facilitated through developing a comprehensive list of roadmap priorities. The Oregon Department of Transportation, ODOT, recently conducted a study evaluating a wide range of CV applications in the areas of V2I safety, V2V safety, agency data, environment, road weather, fee payment, mobility, and smart roadside. Based on this study, ODOT determined which applications were the best compromise of being manageable, requiring low effort, and having a meaningful application (Bertini & Wang, 2016). Traffic network and signals CV applications were determined by ODOT to be effective and relatively easy to deploy. As a result, Advanced Traveler Information Systems (ATIS) were identified as the top technology for ODOT to seek to deploy in the future (Bertini & Wang, 2016). The benefits of ATIS are not geographically constrained. Therefore, it is recommended INDOT prioritize deploying ATIS systems to improve traveler awareness and increase traffic throughput. Furthermore, INDOT should invest in Dynamic Speed Harmonization technology systems in the long term. These systems are likely to have a significant effect in reducing the magnitude of speed differences between vehicles. This will improve driver safety and overall traffic flow.

Moreover, ODOT identified Freight Dynamic Travel Planning and Response systems as being applicable to meet the needs of Oregon's drivers (Bertini & Wang, 2016). These will provide freight planning and performance information to coordinate load movements, reducing empty-load trips. Indiana, with its significant freight traffic, should invest in these systems as well. In addition, ODOT indicated Signal Phase and Timing (SPaT) applications would be impactful to deploy, while requiring minimal effort to do so (Bertini & Wang, 2016). These applications will enhance driver safety, through providing warnings and alerts, and mobility through enabling dynamic and efficient traffic management. SPAT's improvement of vehicle mobility will have a positive impact on the environment through reducing emissions. Given the reality of SPAT's relatively low cost and numerous benefits, INDOT should invest in its deployment to improve its road systems. Lastly, GPS probe devices can be leveraged to monitor traffic in urban areas. ODOT has observed that, through giving transportation authorities a comprehensive depiction of traffic in urban areas, probe devices can improve the optimization of routes (Bertini & Wang, 2016). If warnings are issued promptly to drivers through traffic information stations, vehicles will become more distributed in a manner that alleviates traffic. In urban areas such as Indianapolis and Northwest Indiana, GPS probe device systems are extremely applicable to fulfilling INDOT's mission to improve traffic flow. Hence, they should be identified as a long-term priority.

On the subject of automated vehicles, INDOT can make numerous infrastructure changes to extract benefits out of autonomous vehicles. Roadway construction practices must be standardized and improved. From the conducted interview with Toyota, autonomous vehicles will require clear lane markings and standardized signs. Road construction practices should prioritize these elements for the safe operation of autonomous vehicles. In addition, dynamically changing roadway direction on a situational basis is an autonomous technology that INDOT can leverage to improve traffic flow in urban areas (Katrakazas, Quddus, Chen, & Deka, 2015). For this to be employed with autonomous vehicles, DSRC technology is necessary to communicate lane direction to autonomous vehicles. In addition to dynamically changing roadway directions, lane width can be dynamically changed in conjunction with autonomous vehicles. According to Caltrans, during busy times, lane width information can be communicated to autonomous vehicles. Since AVs have lane centering technology built in, lane width requirements are not as stringent as SAE Levels 0 and 1. For road sections entirely saturated with autonomous vehicles, lane widths can be reduced from twelve to eight lanes to improve traffic flow and throughput during busy times.

Roadmap Priorities for Incorporation of AV/CV Technology. INDOT can prepare for the onset of AVs through adopting several roadmap priorities. The standardization and rulemaking of AV technology is currently ambiguous and inconsistent from a national perspective. To give OEMs more confidence to innovate and move AV technology forward, INDOT should develop a list of clear, consistent standards for AV manufacturers to meet in Indiana. Without such standards, AV OEMs will be discouraged from producing consumer-ready vehicles, as introducing them to markets will be impossible without standards to abide by. Instead, OEMs will continue experimenting with the technology in test facilities. In addition, INDOT can prepare for AVs through improving its infrastructure's marking and signage. Clear lane markings are required by AVs for proper lane centering. Standardized signage is required for sign recognition technology. Both of these features are imperative for AV operation at SAE Levels 2 and above. The benefits of implementing these improvements will also apply to CVs and standard vehicles. Therefore, it is in INDOT's best interest to invest in signage and lane marking improvements.

From the standpoint of CV roadmap priorities, several actions are recommended for INDOT's consideration to improve the deployment of CV technology. These were evaluated on their applicability to infrastructure systems, monetary cost, and time investment required by ODOT (Bertini & Wang, 2016). As state DOT's with similar objectives, the rationale behind ODOT's evaluation of its priorities is relevant to meeting INDOT's needs as well. It is imperative that INDOT develop a communications plan to meet CV communication needs for V2I priorities: ITS, traffic signals, and other INDOT V2I systems (Bertini & Wang, 2016). This is necessary to identify needs and the funds needed to meet each need. Although this plan can be developed in the short term, maintaining it in accordance with the rapidly evolving AV/CV field should be a long-term priority for INDOT. As a long-term action, INDOT should collaborate with USDOT, AASHTO, and other stakeholders to preserve space for DSRC in the spectrum and instill confidence in CV OEMs (Bertini & Wang, 2016). Although 5G technology, a DSRC alternative, has potential to achieve low latency, DSRC is a proven technology that has been developed from significant government investments. Both in the short and long term, the public's expectations for AV/CV technology are unnecessarily high (Bertini & Wang, 2016). These should be tempered through the issuing of accurate information to counteract misperceptions. Altogether, adapting these priorities will help ensure the CV applications INDOT choses to emphasize the deployment of will be instituted.

Integrating AV/CV Technology into Agency Operations. In order to fully incorporate AV/CV technology into its road systems, INDOT must fully prioritize integrating CAV technology into daily agency operations. Without the dedicated personnel to manage the standardization of AV/CV technology and institution of supporting infrastructure systems, INDOT will almost certainly fail in developing a 21st century road network for AV/CV technology. A prime example of an agency that INDOT should model its AV/CV department organization after is the Virginia Department of Transportation (VDOT). VDOT has commissioned a dedicated AV/CV program manager, making Virginia the first state to do so. It is advised INDOT make a similar position in its organization to manage all AV/CV preparation procedures. VDOT also started a state study committee to increase internal awareness about the technology. INDOT should initiate the development of a similar committee for the same purpose. From a national perspective, VDOT is involved in the CV Pooled Fund Study (Center for Transportation Studies, 2018), AASHTO Technical Working Group, and V2I Deployment Coalition. Joining these organizations would immerse INDOT in AV/CV field developments and improve internal awareness of the technology.

Identifying Long-Term Funding Sources for Stability. Identifying long-term funding options to develop DSRC technology across the state of Indiana is imperative to ensuring CVs have the necessary infrastructure in which to operate. It is very common for projects to be derailed or delayed by a lack of funds. For instance, Illinois Department of Transportation's (IDOT) failure to secure funds for the Illiana Corridor halted the project, despite INDOT's commitment to fulfilling its designated project deliverables. Even worse, poor management and fund allocation can halt the project of interest and have a negative impact on other projects through wasted funding. Hence, given INDOT's commitment to updating its infrastructure in preparation for the onset of AV/CV technology, it is absolutely necessary that the organization develop a constructive, long-term financial plan allocating funds for projects identified as key for supporting AV/CV growth and development. To ensure the secure allocation of funds, the source of funding for each project should also be identified.

2.6 Federal Initiatives

2.6.1 NHTSA

2.6.1.1 Rule making. NHTSA in December 2016 proposed a rule that would advance the deployment of connected vehicle technologies in consumer vehicles to prevent crashes. Consequently, vehicles would communicate with others using V2V communication technology. Therefore, the new light cars after the rulemaking would be fully deployed and hence capable of preventing many crashes annually through "talking" to one another. In a statement, the transportation secretary claimed that they were doing everything possible to utilize the technology in saving lives. Thus, the overdue V2V rule was the next in line to achieve road safety. Its adoption was projected to offer 360-degree situational knowledge on the road. It would assist in enhancing vehicle safety. Notably, the new rule would necessitate the automakers to incorporate V2V technologies in the newly made light-duty cars. The proposal is that the V2V devices use a similar communication language via controlled messaging created within the industry.

Furthermore, the proposed V2V devices would utilize the "Dedicated Short Range Communications (DSRC)" to convey data; for instance, communicating about the current location, speed, or direction to the adjacent cars (NHTSA, 2016b). This information would be posted and broadcasted immediately for ten times every second to adjacent cars. As a result, V2V-enabled cars can detect risks and offer warnings to the drivers to avert the likely crashes. The vehicles that would benefit most of this technology are the automated ones with adaptive cruise control and automatic emergency braking.

With the V2V, the driver can get information on time and manage to handle many crash situations. For example, such drivers can make decisions regarding passing on a two-lane road, making a left turn in the same lane with oncoming vehicles or establishing whether a car nearing an intersection seems to be heading to a collision. Here, V2V communications can sense imminent threats from distant locations. This is helpful since a driver cannot use his senses for such kind of detection. Another significant merit is that V2V secures the users' privacy. The technology shuns from exchanging data connected to or that which can be linked to a person. The rule seems to necessitate comprehensive privacy and safety measures in all the V2V devices.

2.6.1.2 Federal Automated Vehicles Policy. The Federal policy acknowledged the great potential offered by V2V and V2I technologies in the transport industry and hence supports to amplify the highly autonomous vehicles (HAVs) revolution. DOTs have been challenged to formulate new methods for ensuring that the technologies are introduced safely, especially given the speed at which the complicated HAVs are coming up. The policy is meant to be agency guidance instead of a rulemaking to increase the speed of delivering the first regulatory model and best practices for directing manufacturers as regards designing, developing, testing, deploying HAVs safely. Therefore, to facilitate this safe introduction and adoption, four tasks have been provided as follows:

Vehicle Performance Guidance for Automated Vehicles. This guidance offers the best practices for Automated Vehicles as concerning the need to predeploy safe designs, develop, and test HAVs before selling or using them on public roads. Notably, deployment is termed as HAV operation an individual not involved in designing, developing, or manufacturing. The objective is to help in testing and adopting HAVs safely (Bertini & Wang, 2016). The guideline formulates the DOT's expectations of the motor industry by offering logical practices and processes, which makes, distributors, and retailers able to adhere to immediately in testing and deploying HAVs. It is important to share the data obtained from the activities to enable the government, motor vehicle sector, and the public to raise their knowledge and comprehension as technology continuously evolves. In so doing, these stakeholders have protection over their legitimate confidentiality and competitive interests.

Model State Policy. Currently, a motorist can drive across state lines without worrying about anything other than the speed limit changing. In this regard, the adoption of HAVs should maintain that freedom. Likewise, automakers should have the capacity to make one HAV fleet instead of 50 dissimilar versions to satisfy the requirements of each state.

State governments are responsible for facilitating HAVs, ensuring that they are securely installed and promoted for their life-saving merits. Thus, the framework makes sure that states preserve their conventional duty for registering cars and getting operational licenses, observing and enforcing traffic rules, as well as, acquiring car insurance and promoting legal responsibility regimes. The American DOT has joined hands the "American Association of Motor Vehicle Administrators (AAMVA)" to survey HAV policies (Bertini & Wang, 2016). The partnership was among the ground for the model policy described here and recognizes where upcoming matters fit in the current state structure. Notably, the common aim is to ascertain the institution of a steady national model instead of a patchwork with incompatible rules.

NHTSA's Current Regulatory Tools. NHTSA has the mandate to continuously use the available control power over HAVs through its current regulatory tools. These tools include interpretations, exclusions, defects and execution power, as well as, notice-and-comment rulemaking. Additionally, NHTSA can check for safety defects thereby enabling the agency to retrieve cars that seem to pose threats even in the absence of any pertinent "Federal Motor Vehicle Safety Standard" (FMVSS).

Another important aspect is that NHTSA has made some new information and advice documents to help controlled groups and the public comprehend how to utilize these tools. Specifically, the document comprises education, practical guidance, as well as, help to groups in need of the tools. Moreover, NHTSA has restructured its process of review and is planning to give easy HAV-associated interpretations for a period of 60 days. It is also thinking about simple HAV-linked indemnity requests in a span of six months.

New Tools and Authorities. Using the recent effective NHTSA control tools will assist in expediting the secure introduction as well as control of the emerging HAVs. Nonetheless, given the current administrative acts and regulations that were formulated when HAVs were just a remote aspect, those tools might be inadequate in promoting the introduction of HAVs safely and realizing the whole safety as promised by the new technologies. The HAVs are developing at a high speed. This added to the complication and newness of these developments is a threat to the existence and survival of the conventional control procedures and capacity of the Agency. As a result, the category of new tools examines the tools, control and authority structures capable of helping in deploying new technologies safely by assisting the agency in increasing its flexibility and nimbleness. Standards and examination protocols grounded on keen scientific study will be vital at all times. Notably, there is a possibility of requiring extra regulatory tools, new expertise, and research to enable the Agency to handle safety issues swiftly and speed up the installation of lifesaving technologies.

2.6.2 FHWA

In 2015, FHWA released the vehicle to infrastructure deployment guidance and products. The guideline is intended to facilitate a smooth and effective deployment path for agencies who are interested in implementing vehicle-to-infrastructure (V2I) technology within a connected vehicle environment. It is not mandatory for public agencies to follow the FHWA guidance, but doing so will support the transition toward the connected vehicle environment (FHWA, 2015).

The deployment guidance covers the following areas:

1. Planning
2. Federal-aid eligibility of V2I equipment and operations
3. Interoperability of V2I deployments
4. Evaluation of the deployments
5. ITS equipment capability and compatibility
6. Hardware/software device certification
7. Reliability
8. Use of existing infrastructures
9. Communication technology
10. Connected vehicle's privacy and security

NHTSA rulemaking (Harding et al., 2014) does not require the V2I deployment as a prerequisite for V2V deployment. However, FHWA V2I deployment guidance can leverage the benefits of V2V technology.

2.6.3 AASHTO

Connected Vehicle Field Infrastructure Footprint Analysis. AASHTO performed this analysis as an effort to assist transportation authorities in their preparation to adopt a connected vehicle future. A revolutionary aspect of a CV future is the ability of the vehicles, mobile items, and infrastructure to link through wireless devices. This is a significant incentive for adopting CV vehicles because it will improve highway safety, traffic efficiency, and lessen the environmental effects of transportation systems.

It is anticipated that the advent of the CV environment will take advantage of the wireless connectivity by leveraging its benefits in different ways. For instance, the number of crashes on the highways will drop drastically given the fact that CV features will enhance driver awareness. In addition, the availability of information pertaining to infrastructure status through CV-linked data will improve the performance of the transport systems. Furthermore, the environmental effects of cars are likely to decrease because CVs can communicate to reduce inefficient stopping.

In collaboration with DOTs and Transport Canada, AASHTO has undertaken a footprint analysis to yield information that agencies can use to make CV-related decisions (Bertini & Wang, 2016). AASHTO's role in this analysis has been achieved via its Connected Vehicle Deployment Coalition. This group is made up of representatives from different states and regional transportation agents. The work comprises the vision intended for a nationwide CV footprint. It also describes the background and present research regarding the connected car deployments. Furthermore, it comprises the assumptions of the analytic infrastructure footprint and application analysis.

AASHTO's footprint analysis comprises nine scenarios. Several of these are rural roadway, urban highway, global land border crossing, DOT processes and maintenance, and smart roadside freight corridor. Another important aspect of footprint analysis is the discussion regarding the possibility of equipping signalized intersections using connected vehicle infrastructure as the first point of determining a countrywide footprint.

AASHTO formulated a to-do-list for making nationwide strategies. Notably, the recognition of particular locations for the deployment of infrastructure for connected vehicles is being prioritized. It also consists of deployment's funding options and address requirements for incorporating connected vehicle activities. Finally, there is a provision for creating procurement documents that must be in line with the deployment guidance made by the federal admin for the future.

2.6.4 V2I Deployment

The V2I Deployment Coalition was conceptualized as a platform so that the stakeholders can discuss the V2I related issues. "Nationwide deployment, operations, and maintenance of V2I applications will require long-term cooperation, partnership, and interdependence between the infrastructure owners and operators (State, County and local level transportation agencies); the automobile industry original equipment manufacturers (OEMs), and aftermarket manufacturers; and a variety of other stakeholders" (Bertini & Wang, 2016; National Operations Center of Excellence, n.d.)

The vision of the V2I Deployment Coalition is to come up with "an integrated national infrastructure that provides the country a connected, safe and secure transportation system taking full advantage of the progress being made in the Connected and Autonomous Vehicle arenas" (National Operations Center of Excellence, n.d.).

The mission of the V2I Deployment Coalition is "to work collaboratively with the industry, state and local governments, academia and USDOT to achieve the goal of deploying and operating a functioning V2I infrastructure" (National Operations Center of Excellence, n.d.).

The objectives of the V2I Deployment Coalition are to:

1. Provide leadership on Connected Vehicle (CV) Program deployment efforts
2. Establish CV deployment strategies
3. Lead and provide support on continued technical research for CV
4. Support CV standards development
5. Provide input to and refinement of CV guidance

2.6.5 ITS JPO

The Intelligent Transportation Systems Joint Program Office (ITS JPO) puts emphasis on intelligent vehicles, intelligent infrastructure and the creation of an intelligent transportation system through integration with and between these two components. The ITS JPO has multiple initiatives, which encourage development of CV applications and their implementation.

Connected Vehicle Safety Pilot. The ITS JPO conducted a pilot for the Connected Vehicle Safety from 2011 to 2013. The reason for designing the Safety Pilot was to support a 2013 NHTSA decision to gather data on system effectiveness and user acceptance. It was also designed to provide an actual operating environment for mobility, safety and the development of environmental applications besides archiving data for further research purposes. Several benefits were expected from this study, including the determination and documentation of the likely benefits of vehicle technologies and evaluating whether drivers accepted safety systems based on cars.

The location of the pilot was at Ann Arbor in Michigan. The following three safety devices were installed in approximately 3,000 vehicles (Bertini & Wang, 2016).

- The Vehicle Awareness Device is an electronic device, which sends vital safety messages (BSM) through a wireless communications link. Its installation does not involve any connection to the systems of the vehicle. The vehicle awareness device is usable in all types of cars.
- The Aftermarket Safety Device refers to a device whose installation in vehicles facilitates in the dissemination and receipt of safety information through DSRC wireless communications. It can issue visible or audio warnings to the driver in case of any incidents.
- The Retrofit Safety Device is usually installed by an authorized service provider. The process of fitting it to a vehicle occurs at a service facility when the operation of manufacturing the vehicle has been completed. The vehicle data bus is connected to the retrofit safety device during installation, hence enabling the provision of accurate information from sensors within the vehicle.

After integration, the final system has a driver interface and can receive and even broadcast BSMs. Besides, this system is also capable of processing these messages for purposes of providing alerts or warnings to the driver of the vehicle that bears the system. The development of these devices is mainly for transit trucks and vehicles. The Integrated Safety System is installed during the vehicle's production process. The system is interconnected with proprietary data buses. It is capable of using sensors in the vehicle to provide accurate information. This inbuilt system can receive and broadcast BSMs. It processes the messages and provides alerts or warnings to the driver of the vehicle containing this system. Integrated safety systems are meant for use in light vehicles, transit vehicles, and trucks.

Through its research, the NHTSA has established that Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) applications are capable of providing solutions for up to 80% of crashes. The main crash types that are responsible for the situations above include rear end warning responsible for 28%, lane departures contributing 23%, and intersections that are responsible for 25% (ITS JPO, n.d.h). Other crashes include lane change at 9%, opposite direction crashes at 2% and back over, which contributes 2% to the scenario as mentioned earlier. The safety pilot demonstrated four V2I applications and eight V2V applications to address the above situations.

The V2V applications include warnings for forward collisions, emergency brake lights, assistance for intersection movement, and signals for lane change and blind spots. Other applications include warnings against passing and turn across paths. The V2I applications include timing and signal phase, curve speed warning, pedestrian detection and railroad crossings. Of note is that the safety pilot had a model deployment with many drivers who responded to warnings and in-vehicle alerts. It has been evaluated independently.

Connected Vehicle Deployment Program. The Connected Vehicle Deployment Program (CVDP) is an initiative by ITS JPO to facilitate safe and networked communication among vehicles, personal communication devices, and infrastructure. The United States Department of Transport (USDOT) sponsors connected vehicle research to apply wireless technology to making surface transportation greener, safer and faster. This program will cover many pilot sites having the different focus, needs, and applications. The CVDP program currently has funding of up to $100 million (ITS JPO, n.d.h). In March 2014, 63 responses were obtained by the USDOT from the private industry and the public regarding connected vehicle technology. The DOT chose three vehicle deployment sites for the first phase of this program. These sites include New York City, Wyoming and Tampa, Florida. These locations have a range of applications involving connected vehicle technologies that cater to site-specific needs.

Wyoming. The CV trial in Wyoming includes the use of connected vehicle technologies in improving the efficiency and safety of truck movements especially along I-80. The deployment uses connected vehicle technology in developing and monitoring Interstate performance. The I-80 corridor in Wyoming is freight-intensive, averaging 11,000 to 16,000 vehicles per day, most of which are heavy-duty trucks. Its approximate length is 402 miles and has a maximum elevation of 8640 feet at the Sherman Summit. The high elevation makes this corridor a subject of winter weather occurrences, especially between October and May. Such events include the covering of road surfaces by ice and snow in addition to the high winds and poor visibility experienced in this area. From 2002 to 2012, 3,470 high-wind crashes occurred (ITS JPO, n.d.h). The pilot program aims to provide applications using vehicle to vehicle and vehicle to infrastructure connectivity in supporting services that improve mobility and safety. These applications will relay direct information to the fleets. Alternatively, similar information can be transmitted to fleet management centers that will then communicate with individual trucks or vehicles. Among the applications deployed are road weather advisories, freight carrier and motorist warnings, and situation awareness among others depending on user needs.

New York. The CV trial in New York aims at improving the safety of pedestrians and travelers using connected vehicle technology (ITS JPO, n.d.h). This objective aligns with New York's Vision Zero Initiative, which aims at reducing pedestrian fatalities hence improving the safety of travelers in the city. This site facilitates the evaluation of CV technology in tight intersections typical of the urban transportation system. The trial will involve the deployment of CV technology and its associated applications in high accident rate areas of Brooklyn and Manhattan (ITS JPO, n.d.h). Some of the applications under implementation include violation warning for red light and signalized crosswalk warning for pedestrians among others. This deployment will provide samples for comparison against those from locations not instrumented. The pilot deployment features the installation of V2V technology in 10,000 vehicles within the city. The high priority corridors of Brooklyn and Manhattan will see an upgrade of traffic signals to facilitate vehicle to infrastructure transmission capabilities.

Florida. The Tampa-Hillsborough Expressway Authority (THEA) will oversee this project. It involves deploying various connected vehicle technologies around the Lee Roy Selmon Expressway. Other features of the deployment area include high pedestrian density, trolley, and bus services among others. Significant delays are commonly experienced in the deployment area especially during peak hours resulting in increased crashes and collisions. The location also experiences pedestrian conflicts, transit signal delays, and signal coordination issues (ITS JPO, n.d.h). This exercise aims to reduce congestion, especially during peak hours. Additionally, various V2V and V2I technologies will be applied to improve safety and mobility of motorists and the pedestrians. These applications are expected to create reinforcing advantages for drivers, transit operation, and even the pedestrians. Among the applications under deployment are curve speed warnings, intersection movement assist, and transit signal priority.

The Connected Vehicle Pilot Deployment Program roadmap is shown in Figure 2.2 (Hartman, n.d.). There is anticipation for future trial programs to which states might consider submitting proposals.

Smart City Challenge. In 2015, "Beyond Traffic: The Smart City Challenge," was issued by USDOT offering up to 40 million dollars of federal funds to mid-sized cities for conducting smart city demonstrations. According to the program, states should exhibit the manner through which intelligence in roads and the use of technological data tools can assist in lowering congestion, improving safety, and protecting and supporting the vitality of the environment. The ideal features of a smart city as determined by the USDOT include that the population should range from 200,000 to 850,000 people as per the 2010 census. The urban center should have a dense population typical for any mid-sized city in America (ITS JPO, n.d.h). It should represent more than 15% of the total population of the urbanized area as per the 2010 census data.

The locality should have a public transportation system. Its environment should promote the demonstration of the proposed strategies. The urban center

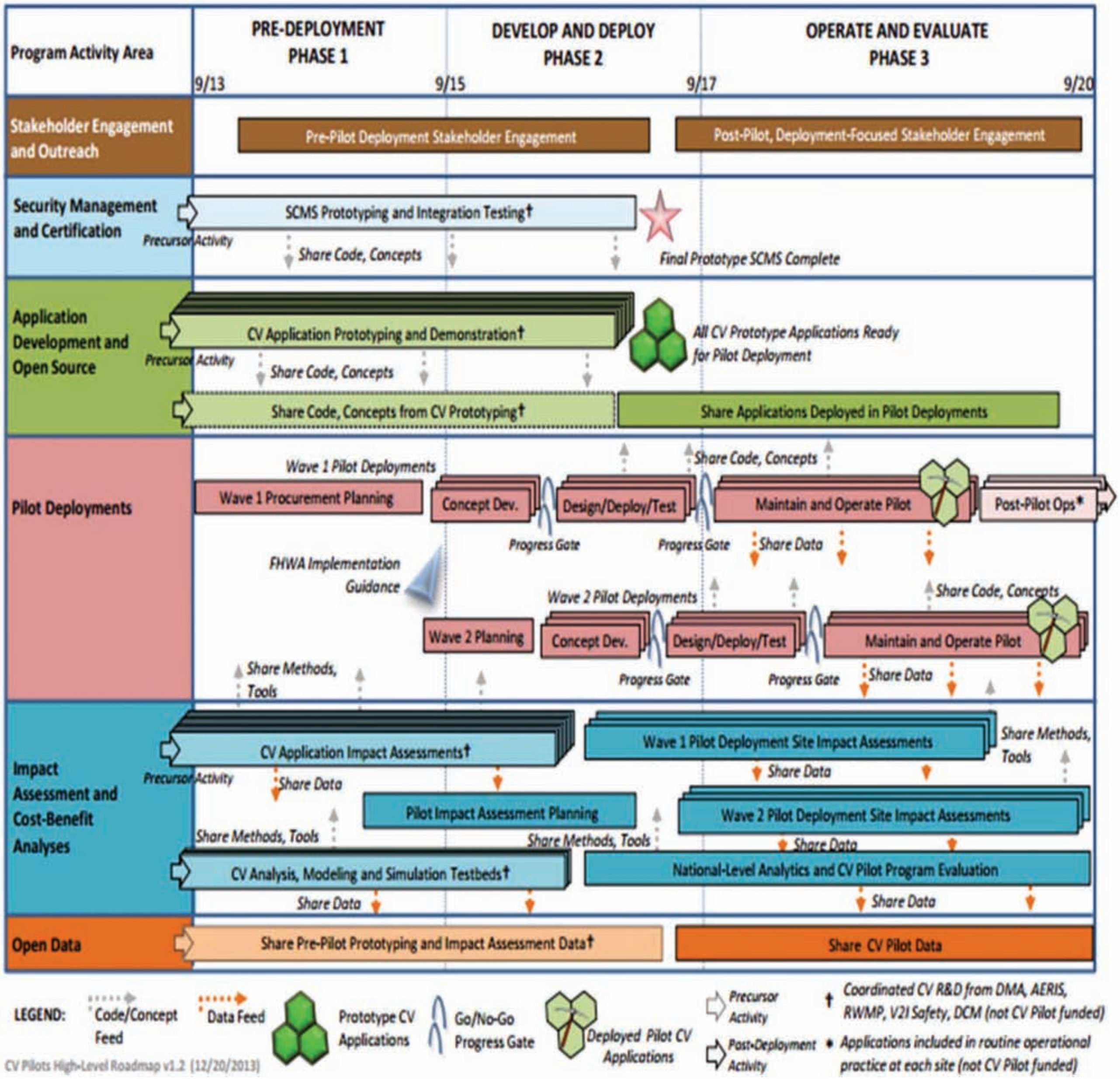


Figure 2.2 Connected Vehicle Pilot Deployment Program roadmap (Hartman, n.d.).

should commit to integrating with sharing economy. The city should show determination to make machine-readable data accessible and discoverable. The same should also be usable especially for purposes of innovation and entrepreneurship.

Some of the desirable smart city technology elements as identified by the DOT include urban automation and intelligent infrastructure that is based on sensors and connected vehicles. This department has also outlined various features of a smart city including the standards and architecture of the city, smart land use and efficient information and communication technology (ITS JPO, n.d.h). Among the innovative approaches as outlined by the DOT includes urban analytics, delivery and logistics, and involved citizens. The process of roadway electrification and subsequent presence of electric cars is also an innovative approach. Other approaches besides those mentioned above include partnering opportunities and strategic business models.

The Smart City Challenge attracted 1400 participants with collaborating interest being expressed by up to 300 companies. In March, the list of seven finalists was announced. Each finalist automatically received an award of 100,000 dollars in addition to technical guidance and assistance from Vulcan and USDOT (ITS JPO, n.d.h). The eventual winner of $40 million in federal funds was Columbus Ohio, as announced in June 2016.

2.6.6 FMCSA

The Federal Motor Carrier Safety Administration (FMCSA) is in charge of providing organizational safety data as well as relevant services to transport industry. It is possible to access information by just searching the FMCSA database. The services offered include registering for a USDOT number, paying fines through the website, and ordering firm safety profiles. The other services are challenging FMCSA data with the help of the DataQs system, accessing the Hazardous Material Route registry, and obtaining the National Crash and Out of Service rates meant for use in the Hazmat Permit Registration (FMCSA). Finally, the other services entail obtaining registration forms that can be printed and locating information regarding additional information systems for FMCSA. When using the database, it is important to note the need for a unique USDOT number meant for the PIN required for gaining access to the system.

2.6.7 National Cooperative Highway Research Program (NCHRP)

2.6.7.1 Project 20-24(98). NCHRP started the project 20-24 (98) to look at the issues that will be faced by the state and local agencies when dealing with the connected and autonomous vehicles. As a part of the project's deliverable, a connected/automated vehicle research roadmap was developed to address the policy, planning and implementation issues. The project focused on four general subject clusters (Shladover & Gettman, 2015):

1. Institutional and policy
2. Infrastructure design and operations
3. Planning
4. Modal application (transit, trucking)

Under these four broad categories, the report identified 23 projects (Shladover & Gettman, 2015).

2.6.7.2 Project 20-102. NCHRP also initiated a project 20-102 which is responsible for maintain the roadmap from project 20-24(98). The project 20-102 is currently active and includes the following tasks (NCHRP, n.d.)

1. Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems into Market Decisions
2. Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations
3. Challenges to CV and AV Application in Truck Freight Operations
4. Strategic Communications Plan for NCHRP Project 20-102
5. Road Markings for Machine Vision
6. Implications of Automation for Motor Vehicle Codes
7. Dedicating Lanes for Priority or Exclusive Use by CVs and AVs
8. Providing Support to the Introduction of CV/AV Impacts into Regional Transportation Planning and Modeling Tools
9. Cybersecurity Implications of CV/AV Technologies on State and Local Transportation Agencies
10. Mobility-on-Demand and Automated Driving Systems: A Framework for Public-Sector Assessment
11. Business Models to Facilitate Deployment of CV Infrastructure to Support AV Operations
12. Planning Data Needs and Collection Techniques for CV/AV Applications
13. Data Management Strategies for CV/AV Applications for Operations
14. Impacts of Connected and Automated Vehicle Technologies on the Highway Infrastructure
15. Preparing TIM Responders for Connected Vehicles and Automated Vehicles
16. Deployment Guidance for CV Applications in the Open Source Application Development Portal
17. Minimum Safety Data Needed for Automated Vehicle Operations and Crash Analysis
18. Update AASHTO's Connected Vehicle/Automated Vehicle Research Roadmap
19. Infrastructure Modifications to improve the Operational Domain of Automated Vehicles
20. State and Local Impacts of Automated Freight Transportation Systems
21. Infrastructure Enablers for Connected and Automated Vehicles and Shared Mobility—Near-Term and Mid-Term

3. SYNTHESIZING THE WORK OF OTHER STATE DOTS

3.1 Region 1

3.1.1 Massachusetts

3.1.1.1 Autonomous Vehicles

3.1.1.1.1 Testing of AV. In the past, Cambridge Systematics has researched the implications AVs have had on infrastructure planning.

3.1.1.2 Connected Vehicles

3.1.1.2.1 Vision. Scott Smith of USDOT in Boston indicated that AV/CV technology development would occur in an evolutionary manner. For CVs, their evolution will depend on the public sector, as rule-making mandating their standardization and implementation would rapidly expedite the rate at which CV technology is introduced. For AVs, Smith sees the introduction of higher, more automated levels as occurring in the future. Levels of low automation will precede their introduction due to less associated complications.

3.1.1.2.2 Objectives. Smith noted the technology is being used to improve vehicle safety.

3.1.1.2.3 Initiatives. For safety, driver awareness can be improved through CV technology's use of sensors and warnings. However, low latency is necessary for CVs to operate effectively, as small delays in message times will result in accidents. USDOT is working on this.

3.1.1.2.4 ***Planning***. Smith does not mention any future plans for USDOT in Boston regarding CV research and implementation.

3.1.1.2.5 ***Challenges***. From a national perspective, there have been a lack of bandwidth standards for regional DSRC systems. This will hamper CV interoperability unless proper rulemaking intervenes. In addition, there are privacy and cyber security issues for connected vehicle implementation. These need to be resolved to advance CV development towards becoming commercially viable.

3.1.1.2.6 ***Opportunities***. Smith indicated DSRC technology offers the required latency for CVs to operate effectively, giving them the opportunity to save lives if other factors, such as rulemaking and spectrum issues, are resolved to facilitate their development.

Takeaways for INDOT:

- INDOT should prepare for an evolutionary path for CVs.
  - Smith sees the analysis of CVs as being too optimistic.
  - They are going to take a significant amount of time to fully implement.
- The public and private sector should collaborate in standardizing CVs.
- INDOT should leverage the private industry's resources through sharing funding with automakers to construct a testbed in Indiana.

3.2 Region 2

3.2.1 New York

3.2.1.1 Autonomous Vehicles

3.2.1.1.1 ***State of legislation***. The state of New York has enacted the bill SB 2005 on April 20, 2017. This bill "allows the commissioner of motor vehicles to approve autonomous vehicle tests and demonstrations. Requires supervision from the state police for testing. Specifies requirements for operation, including insurance of five million dollars. Defines autonomous vehicle technology and dynamic driving task. Requires a report on testing and demonstration."

3.2.1.1.2 ***Testing of AV***. The state of New York allows the testing of AVs but requires the supervision from the state police. Afterwards the OEMS need to report the AV testing to the state.

3.2.1.1.3 ***Results or findings***. New York is accepting applications from the OEMs who are interested to test their vehicles. However, no AV testing has been reported at the time of writing this report.

3.2.1.2 ***Connected Vehicles***. We interviewed Mr. Richard McDonough from New York State Department of Transportation (NYSDOT) and asked for his views on the evolution of connected vehicle technology.

3.2.1.2.1 ***Vision***. In 2014, New York City (NYC) began its *Vision Zero* initiative to reduce the number of fatalities and injuries resulting from the traffic crashes. Mr. McDonough emphasized CV technology's continued evolution. However, McDonough is convinced its deployment lies in the distant future. He argued there is no CV system in the world ready to be deployed on a commercial scale.

3.2.1.2.2 ***Objectives***. NYSDOT plan to deploy the technology to improve safety and mobility of New York State's roads.

3.2.1.2.3 ***Initiatives***. For mobility purposes, NYSDOT is researching the extraction of data from vehicles with DSRC radios. This will allow them to know where queues are occurring and gather local information to improve road management. As far as safety is concerned, NYSDOT is monitoring driver behavior in CVs. This can allow drunk drivers to be detected and other drivers to be alerted to their presence.

3.2.1.2.4 ***Planning***. For safety purposes, NYSDOT is not limiting themselves to CV implementation. They believe accidents are due to human error, which can never be eliminated unless the driver is removed from the vehicle's operation. Due to the complex nature of automated vehicles, any perceptible impacts from these will be seen only far into the future according to McDonough.

3.2.1.2.5 ***Challenges***. A national level challenge McDonough believes faces all implementers of the technology is the ineffectiveness of non-connected autonomous vehicles. He is convinced both systems must be integrated for a situationally aware autonomous vehicle to be created. In order to address this challenge, McDonough believes legislatures should force autonomous vehicle makers to incorporate connected systems into their vehicles. In addition, nationally CV hardware is not standardized across the country. Hence, interoperability is a concern. A mandate for 5.9 GHZ DSRC radios would rectify this, but it has not been passed yet.

3.2.1.2.6 ***Opportunities***. NYSDOT sees the potential to standardize DSRC technology and install a radio unit on every vehicle. He identified the price of a device as $500, which makes DSRC's installation by car manufacturers easy to mandate. This is the only way to ensure every consumer enjoys the benefits of CV technology. Because of this potential rulemaking, road systems can be made safer and more efficient through widespread information sharing and movement optimization.

Takeaways for INDOT:

- INDOT is recommended to join the CV Pooled Fund Study.
  - Will allow INDOT officials to sit on project teams, go to meetings, and see field demonstrations of the technology.
- Due to uncertainties behind rulemaking, INDOT should wait for the 5.9 rulemaking to pass before making a decision to deploy CV technology.

3.3 Region 3

3.3.1 Virginia

3.3.1.1 Autonomous Vehicles

3.3.1.1.1 State of legislation. In terms of legislations, Virginia has passed only one bill, HB 454, which allows the driver to look at a visual display while the vehicle is controlled autonomously.

3.3.1.1.2 Testing of AV. The Virginia Automated Corridors were established by the Virginia Tech Transportation Institute in partnership with the Virginia Department of Transportation; the Virginia Department of Motor Vehicles; Transurban; and HERE, a high-definition Nokia mapping business. The Virginia Automated Corridors will help facilitate the use of state roads and test facilities for automated-vehicle testing, certification, and migration towards deployment. Automated-vehicle stakeholders testing in Virginia are not required to obtain a bond; licensing and insurance will be provided through the Commonwealth.

3.3.1.2 Connected Vehicles. Virginia Department of Transportation's (VDOT) FY16 business plan calls for the statewide-connected vehicle program plan to maximize the "safety" and "operational" benefits of these technologies. We have had an opportunity to talk with Virginia Lingham, Melissa Lance, and Dean Gustafson from VDOT.

3.3.1.2.1 Vision. VDOT has been working on iterative improvements to its AV/CV infrastructure program. The nature of these improvements is evolutionary.

3.3.1.2.2 Objectives. Improving infrastructure through minimizing traffic fatalities and inefficiencies is the critical reason behind VDOT's investments into AV/CV technology.

3.3.1.2.3 Initiatives. Administratively, VDOT has commissioned a dedicated AV/CV program manager, making Virginia the first state to do so. From an application standpoint, VDOT has deployed over 3000 DSRC devices across Virginia. Numerous CV applications, such as improving work zone safety, collecting road condition data, and curve speed warning systems are being tested. VDOT believes AVs must be connected to give them the awareness necessary to function safely.

3.3.1.2.4 Planning. In the future, VDOT would like to collaborate with other agencies in developing a national data cloud to hold all states' testing data. This will ensure freedom of information and expedite the technology's development. In addition, VDOT is not restricting themselves to DSRC technology, 5G experiments will also be performed. 5G offers the key advantage of requiring less saturation with a minor increase in latency. 5G used outside intersections will be integrated with DSRC deployed at intersections in the system to be tested by VDOT.

3.3.1.2.5 Challenges. A national level problem relating to AV/CV implementation is detail mapping on roads, which is currently not at the levels required by AV/CVs. Quality lane markings, provided curve geometry, real time work zone information updates, and real time lane closure information updates are several examples of required improvements in detailed mapping. From a regional perspective, CVs are not standardized. Interoperability issues across regions may emerge without the standardizing legislation.

3.3.1.2.6 Opportunities. VDOT sees an opportunity to extract benefits from CV technology in the near future, even with a mixed fleet of connected and non-connected vehicles. An example of this is CV-enabled collision warnings.

Takeaways for INDOT:

- INDOT should start its own state study committee to increase awareness about the technology.
- Engaging in national initiatives, such as the CV Pooled Fund Study, AASHTO Technical Working Group, and V2I Deployment Coalition, would keep INDOT updated on recent developments relating to AV/CV technology.
  - INDOT would be able to utilize the technology to meet its needs in a more effective manner.
- To capture the advantages of AV/CV technology, INDOT should identify key weaknesses in its road system and determine connected vehicle applications that can rectify the issues.

3.4 Region 4

3.4.1 Florida

3.4.1.1 Autonomous Vehicles. The state of Florida has made significant strides in actualizing its vision for deploying autonomous technology and autonomous driving. In fact, it is one of the few states in the US where true self-driving is allowed. This progress puts Florida in a leadership position as far as legislation on the use of autonomous technology is concerned.

3.4.1.1.1 State of legislation. Between 2012 and 2016, the lawmakers have enacted laws that support the use of driverless cars for study purposes, the designation of proving grounds and facilitation of the planning for their use in the public transport system. There are many enacted pieces of relevant legislation including HB 1207, HB 599, HB 7027, and HB 7061 among others (National Conference of State Legislatures, 2017). These define AV and issues pertaining to their safety, testing, and operation.

3.4.1.1.2 Proactiveness. The progress that has been made began with legislative action five years ago, when it became legal to test motor vehicles with autonomous technology on public roads. The lawmakers in Florida had the foresight to encourage the development of this innovation without compromising road safety. Thus, it became mandatory that a person possess a valid driver's license, which authorized them to operate an autonomous car for testing purposes. Additionally, the lawmakers noted that it was necessary for such drivers purchase a self- insurance or a safety bond to prior to the test activity. Also, it was important that the results of tests be submitted to the Department of Highway safety and motor vehicles. The Findings constituted part of a report that would inform additional legislation or regulatory action to facilitate the realization of autonomous driving. Four years later, in 2016, the committed support from the law makers made it possible to enact a bill that eliminates the requirement that a driver must be present in a vehicle if it meets the applicable federal safety standards and regulation.

3.4.1.1.3 Testing of AV. With so much legislative progress, interested parties have the opportunity to conduct more tests so that one day it may be possible for residents of Florida to own and use autonomous cars for private and commercial purposes. In April 2016, another law was made to allow for the study of driver-assistive truck platooning technology. The legislation also allowed that a pilot project be conducted upon the completion of the study (National Conference of State Legislatures, 2017). Such support reveals that all stakeholders in Florida are committed to the vision that the state becomes the leading test bed for autonomous technology. The federal government is supporting the innovation by funding the Tampa-Hillsborough Express Authority in efforts to actualize the use of autonomous vehicles.

Florida and the federal government are working together to usher a new future where active driving will be a thing of the past. The Central Florida Automated Vehicle Partners is working closely with the U.S. Department of Transportation to prove that automated vehicles can become a reality in public transportation. Although the timeline for testing the driverless vehicles on public roadways has not yet been set, the city officials are optimistic that the activity will take place on the states LYMMO routes downtown (LYMMO is a Bus Rapid Transit (BRT) service operated by Central Florida Regional Transportation Authority). The plan is to begin tests on the driver-assisted cars before proceeding to the driverless cars.

3.4.1.2 Connected Vehicles. We had the opportunity to discuss with Mr. Robert Frey, Planning Director at Tampa Hillsborough Expressway Authority, his views on connected vehicles. As an independent agency of the state, the Tampa Hillsborough Expressway (THEA), maintains and operates four facilities within Hillsborough County: The Lee Roy Selmon Expressway, the Brandon Parkway, Meridian Avenue, and the Selmon Greenway.

3.4.1.2.1 Vision. Based on his observation that the development of AV technology has taken the automakers more than 40 years to develop, Mr. Frey believes that the path to connected vehicle development will be evolutionary.

3.4.1.2.2 Objectives. The THEA's main objective for employing the technology is improving driver safety. Accidents are a significant problem in the Tampa area.

3.4.1.2.3 Initiatives. Concerning AV/CV implementation, THEA is still in the design phase. Hence, no initiatives have been conducted thus far.

3.4.1.2.4 Planning. THEA plans to implement connected vehicle technology on a corridor of Tampa expressways starting in April 2018. The technology will initially be present in 1600 vehicles that use the expressway daily. These vehicles will have access to numerous CV-related features, including intersection entry assist, forward collision warning, and curve speed-warning systems. The scale of the technology's deployment will be increased if it improves safety.

3.4.1.2.5 Challenges. THEA faces numerous challenges in implementing CV technology on its road systems. Most notably, it will be difficult to incorporate connected vehicles in sparse numbers. THEA's studies indicate that 40% of vehicles on a road have to be connected for speed harmonization benefits to appear at their lowest level. This problem confronts agencies at the national level; it is not unique to Florida's expressways. From a regional standpoint, THEA is incentivizing consumers to equip their vehicles with CV systems for testing purposes. Getting test samples will be difficult as the testing expands in scale.

3.4.1.2.6 Opportunities. THEA sees great opportunity to use CV technology to safely implement reversible lanes. Currently, drivers face difficulties in identifying the direction of reversible lanes. Their awareness in this regard can be improved with CV guidance. Furthermore, THEA believes its transit vehicles can be made safer with CV-enhanced vehicle turning detection for the driver's blind (right) side. Crashes during right turns comprise 80% of Tampa's transit bus accidents and can be minimized with this technology.

Takeaways for INDOT:

- To ensure data privacy, INDOT should treat CV data like data collected from toll roads.
    - Acquire all necessary information from the data, and then delete it.
- To get consumers to take part in CV pilot programs, offer tolling or tax incentives.

3.4.2 North Carolina

3.4.2.1 Autonomous Vehicles. The 469 Bill defines an AV as any car that can perform devoid of tactical functions as well as instant operations on the road without the need of a driver. The driver should possess a license whereas the vehicle has to be registered. Minors below 12 years cannot ride an autonomous vehicle in North Carolina (Whitney Law Firm, 2017). The law regarding seat belts must be followed to the letter. The operator should take charge in the event of a crash by stopping it and communicating with the law enforcing agencies. The failure to do so is an attraction for punishment.

3.4.2.1.1 State of Legislation. The House Bill 469, which is a regulation for Autonomous Vehicles, which came to being after being passed by the North Carolina House back in April 2017 (Whitney Law Firm, 2017). The vote was a success by a ratio of 119 to 1. After passing, it was issued for Senate review as well as vote. At the moment, the bill is in the hands of the Transportation Committee chamber.

3.4.2.1.2 Proactiveness. North Carolina is still preparing itself for the self-driven vehicles. Currently, it is putting in place measures regarding the same. Many speculations have been made since the passing of the Bill in April 2017 (Jones, 2016). Therefore, it is just a matter of time and it will be clear the way forward regarding the proactiveness of the said legislation and its impact when in use.

3.4.2.1.3 Testing of AV. It is hoped that the proposed regulations regarding AV will attract testing in North Carolina. In case the Bill is made law, the state will be required to formulate formal laws for AV for the first time.

3.4.2.2 Connected Vehicles

3.4.2.2.1 Vision. Mike Holder, Chief Engineer at North Carolina Department of Transportation (NCDOT) believes that connected technology will take its time to fructify and it will be a while before we see fully functional connected applications deployed.

3.4.2.2.2 Objectives. NCDOT will use the technology to improve the safety, capacity, and traffic laws of its roads.

3.4.2.2.3 Initiatives. NCDOT has partnered with its state research universities to complete projects on CV technology. In addition, NCDOT has collaborated with other states in the I-95 corridor coalition. This coalition meets on a quarterly to semi-annually basis with the purpose of discussing new technologies and information. A large majority of recent discussions have been related to CVs.

3.4.2.2.4 Planning. NCDOT's major plan is to construct a test bed in the Research Triangle by the end of 2017. Volvo's truck division and other freight carriers will be the initial users of the test bed. They will be evaluating truck platooning's practicality. Furthermore, NCDOT has been approached by Toyota, Nissan, and GM about permitting their usage of the test bed.

3.4.2.2.5 Challenges. A national-level problem threatening the test bed's operation is the lack of rule making by the FHWA. NCDOT does not know whether they are making decisions that are permissible and in accordance with the law. From a regional standpoint, NCDOT is facing structural challenges. They do not have a specific AV/CV unit, which Mr. Holder sees a need for in the future to manage their test bed.

3.4.2.2.6 Opportunities. NCDOT sees opportunities to work with other states on the East Coast to revolutionize their transportation networks with CV technology.

Takeaways for INDOT:

- INDOT should strongly consider following NCDOT and accepting the SPaT challenge to gain a strong introductory level of knowledge on AV/CV technology.
- INDOT should leverage Indiana's strong research universities to get assistance in learning about AV/CVs through research projects.

3.5 Region 5

3.5.1 Michigan

3.5.1.1 Autonomous Vehicles

3.5.1.1.1 State of Legislation. Michigan enacted the legislation for autonomous vehicles under bill numbers SB 995, SB 996, SB 997, SB 998, SB 169, and SB 663. Michigan legislation specifically outlines and defines terms such as "automated technology," "automated vehicle," "automated mode," and "automated driving system." Legislation also addresses the liability issues when a modification is carried out in the automated vehicle.

3.5.1.1.1.1 SB 995 (2016). This bill was enacted on and "allows for autonomous vehicles under certain conditions. Allows operation without a person in the autonomous vehicle. Specifies that the requirement that commercial vehicles maintain a minimum following distance of 500 feet does not apply to vehicles in a platoon."

3.5.1.1.1.2 SB 996 (2016). Enacted and chaptered on Dec. 9, 2016, this bill "allows for autonomous vehicles under certain conditions. Allows operation without a person in the autonomous vehicle."

3.5.1.1.1.3 SB 997 (2016). Enacted and chaptered on Dec. 9, 2016, this bill "defines automated driving system. Allows for the creation of mobility research centers where automated technology can be tested. Provides immunity for automated technology manufacturers when modifications are made without the manufacturer's consent."

3.5.1.1.1.4 SB 998 (2016). Enacted and chaptered on December 9, 2016, this bill "exempts mechanics and repair shops from liability on fixing automated vehicles."

3.5.1.1.1.5 SB 169 (2013). Enacted and chaptered on December 20, 2013, this bill "defines 'automated technology,' 'automated vehicle,' 'automated mode,' expressly permits testing of automated vehicles by certain parties under certain conditions, defines operator, addresses liability of the original manufacturer of a vehicle on which a third party has installed an automated system, directs state DOT with Secretary of State to submit report by Feb. 1, 2016."

3.5.1.1.1.6 SB 663 (2013). Enacted and chaptered on Dec. 26, 2013, this bill "limits liability of vehicle manufacturer or upfitter for damages in a product liability suit resulting from modifications made by a third party to an automated vehicle or automated vehicle technology under certain circumstances; relates to automated mode conversions."

3.5.1.2 Connected Vehicles. We interviewed Ms. Debra Bezzina from the University of Michigan.

3.5.1.2.1 Vision. Michigan see vast potential in AV/CV. They believe it can have groundbreaking implications on the transportation industry.

3.5.1.2.2 Objectives. Michigan's main objective is the improvement of vehicle safety. They have conducted numerous tests on safety applications of the technology for this reason.

3.5.1.2.3 Initiatives. The University of Michigan's most significant initiative has been constructing a test bed that is currently the world's largest connected vehicle deployment, with a capacity of approximately 1500 connected vehicles. At the test bed, researching the human factors related to AV/CVs is being emphasized. This includes getting AVs to behave more human-like while driving, enabling them to be integrated into current road systems. In the past, the university conducted a safety pilot deployment project consisting of 2,300 vehicles. Data was collected and analyzed from these vehicles' performance when integrated with an array of CV technologies, including forward collision warning, curve speed warning, and emergency electronic brake light systems.

3.5.1.2.4 Planning. In the future, the University of Michigan plans to expand its test bed to include 2300 vehicles. Bezzina deems the test bed's technology adequate due to its success in operating at a large scale. Hence, only a few future improvements will be made to the test bed's fundamental systems. The primary future change to the test bed will be an increase in the scale of what testing is being conducted, which will require additional supporting devices.

3.5.1.2.5 Challenges. Michigan sees a national level problem pertaining to consensus building among various stakeholders in the AV/CV field. The technology will advance faster and be implemented more effectively if there is consensus among OEMs, DOTs, universities and the public.

3.5.1.2.6 Opportunities. The main opportunities are in the area of safety. According to her, AV/CV applications can improve consumer safety and decrease deaths on the road.

Takeaways for INDOT:

- INDOT should rely on Indiana's university system for assistance in conducting relevant research.
    - The amount of research required to properly develop AV/CV technology is overwhelming for state DOTs to conduct single-handedly.

3.6 Region 8

3.6.1 Utah

3.6.1.1 Autonomous Vehicles

3.6.1.1.1 State of Legislation. Policy surrounding AVs is ambiguous and needs to be dealt with. However, Utah DOT (UDOT) believes the technology will come to fruition whether it is encouraged through standardization or not.

3.6.1.1.2 Proactiveness. UDOT is planning to look closely at its state laws and regulations and is considering changing them for AVs. In particular, the areas of vehicle licensing, driver training, and law enforcement need to be improved. UDOT modified state law to allow for truck platooning testing.

3.6.1.1.3 Testing of AV. UDOT has a testbed primarily for CV work, but it is open to using it to test AV technology in the future.

3.6.1.1.4 Results or Findings. UDOT has projected that, in the future, AVs will necessitate new transportation planning. Instead of commuting in their own vehicles, a portion of the population will commute in AVs. The logistics of this process are very complex and need to be determined by DOTs across the nation. For instance, it is unknown whether AVs will decrease the demand of urban parking, transit, or vehicles in general. UDOT believe AV manufacturers are not expecting them to modify existing infrastructure and are designing to operate with existing road striping, signs, etc. Lastly, UDOT is convinced uniform national standards would expedite the development of AV technology through increasing interoperability.

3.6.1.2 Connected Vehicles

3.6.1.2.1 Vision. Leonard and UDOT are convinced AV/CV technology will have a dramatic impact on how people drive, what people drive, and whether they will drive at all in the future.

3.6.1.2.2 Objectives. UDOT primarily seeks to enhance driver safety on its roads. Ultimately, they are striving to achieve zero fatalities. In addition, mobility applications are also being implemented to improve traffic efficiency.

3.6.1.2.3 Initiatives. UDOT has explored numerous initiatives in the area of CV technology. A connected vehicle corridor, consisting of 30 intersections, was constructed. This can provide transit signal priority using DSRC and MMITSS software.

3.6.1.2.4 Planning. In the future, UDOT is planning to enhance the safety applications tested in its connected vehicle corridor. Systems intended to accomplish this include intersection collision avoidance and freeway emergency brake light warning technologies. From a mobility standpoint, the constructed CV corridor will be expanded by spring 2018 to accommodate the testing of mobility applications. UDOT plans to retrofit its transit buses with CV technology to improve their timeliness and reliability.

3.6.1.2.5 Challenges. UDOT faces numerous challenges pertaining to CV technology. From a regional standpoint, Utah DOT will progressively need to make organizational changes to manage its CV initiatives as they become larger in scale. The lack of standards at the national level is causing interoperability issues that are hindering CV technology.

3.6.1.2.6 Opportunities. On the mobility side, UDOT believes it can improve transit schedule reliability with CV applications. Furthermore, UDOT can extract traffic pattern data from CVs. It is foreseen that this data can be implemented to manage traffic and facilitate vehicle platooning. From a safety perspective, UDOT sees potential in the technology to improve driver awareness. UDOT believes it can reduce driver fatalities to zero if properly implemented.

Takeaways for INDOT:

- The sooner INDOT starts testing CV applications, the better prepared it will be to manage the technology and extract benefits from it.
  - The applications have a steep learning curve and take time to progress through.
- Proper management of the technology will require expertise in knowledge outside Civil Engineering.
  - UDOT had to hire numerous experts in ECE, systems engineering, and systems operations to operate its CV technology.

3.7 Region 9

3.7.1 California

3.7.1.1 Autonomous Vehicles. California allows automated cars on its roads for the sake of research. A draft for AV deployment regulations has been issued by the country's motor vehicle department (DMV) for public comment. It seems to be the next phase in permitting the public to use self-driving cars on the nation's roadways.

3.7.1.1.1 State of legislation. The draft regulations are meant to promote the progressive creation of AV technology in the country at the same time converting testing by manufacturers to adoption of self-driving vehicles (Bertini & Wang, 2016). Future public forums should collect the input of the interested stakeholders including the users, scholars, industry, and public to assist in improving the value of the guidelines, which will ultimately be used to operate the self-driven cars.

3.7.1.1.2 Proactiveness. DMV has drafted new regulations to address the future of using AV by the public. The new requirements address complicated questions associated with car safety, operator duties, privacy, certification, as well as, cyber-security. The principal aspects include certification, licensed driver, and permit.

3.7.1.1.3 Testing of AV. According to Chapter 570 of the 1298 Senate Bill, the 2012 Statutes, the DMV was asked to take up guidelines controlling the testing and utilization of AV on public roads. The Bill determined some definitions, which will direct the creation of regulations in the department. Some examples include AV implying technology, which can drive a car without the vigorous physical control or human scrutiny (Bertini & Wang, 2016). Later in September 2014, the DMV made an announcement regarding manufacturers' need to test the cars. Since December 2015, the DMV has given permits to 11 entities including Google, Mercedes Benz, and Nissan to mention but a few.

3.7.1.2 Connected Vehicles

3.7.1.2.1 Vision. We had the opportunity to talk with Greg Larson, Office Chief, Office of Transportation Research at Caltrans. Mr. Larson believes CVs will be introduced gradually in an evolutionary manner. He referenced Caltrans's research since the early 1990s and how the technology and their research have evolved since then.

3.7.1.2.2 Objectives. Caltrans seeks to improve the safety and mobility of the road systems it operates, interstates, US highways, and state routes, through implementing the technology.

3.7.1.2.3 Initiatives. One of Caltrans' initiatives in the area of mobility is the implementation of transit signal priority in urban areas. This technology is an application that gives transit busses an early green or extended green if they are at an intersection to pass. In addition, they are working with the Santa Clara PTA to enable expedited departure to save fuel. This is estimated to save up to 3% in fuel—a huge savings for large-scale vehicle operations. As far as safety is concerned, Caltrans is researching the impact DSRC radios can have on intersection safety. Red light violation warnings are an example of this.

3.7.1.2.4 Planning. Caltrans aims to improve its CV technology through software improvements. Large-scale changes to the nature of the technology are not needed because it has been developed over the years to a nearly operational status.

3.7.1.2.5 Challenges. Caltrans only controls 10% of all roads in California. Hence, a regional challenge faced by Caltrans is reaching out to local transportation authorities in California that control the other 90% of roads, such as cities and small towns, and helping them adapt to AV/CVs. This challenge is a national level problem as well, since all state DOTs control only a portion of their respective state's roads.

3.7.1.2.6 Opportunities. Outside of the widely indicated improvements to safety and mobility resulting from AV/CV initiatives, the 3% fuel savings from expedited departure is seen by Caltrans as a significant potential benefit of AV/CV technology. Although 3% appears to be a minor savings, applied to a population of vehicles, this will be of enormous magnitude.

Takeaways for INDOT:

- Larson mentioned most of the states around Indiana are involved in the CV Pooled Fund Study.
- To avoid falling further behind technologically, he recommends getting involved in that.

3.7.2 Arizona

3.7.2.1 Autonomous Vehicles. Arizona has authorized the operation of self-driven vehicles within its public sphere.

3.7.2.1.1 State of Legislation. Firms are required to use the public highways just as their private labs as a sign of responsibility (National Conference of State Legislatures, 2017). Passengers are free to ride in self-driven cars. There are no extra regulations for governing AV testing since the governor believes that drivers are capable of taking over in case of an emergency. However, they monitor the process keenly. There is a possibility of launching a system for monitoring the accident reports in the local police files that involve AVs.

3.7.2.1.2 Proactiveness. Arizona has developed its own systems and is performing self-driving tests. The state's faith in AV safety is so extensive that no stringent legislation has been passed.

3.7.2.1.3 Testing of AV. Testing of AVs is allowed on Arizona public roads. In support of this, Governor Doug Duey passed an executive order during the end of August 2015 meant to direct agencies in taking the prerequisite steps in assisting the testing process plus the operation of the AVs within the state's public roads. An order was issued permitting pilot projects to be undertaken at appointed universities (National Conference of State Legislatures, 2017). Rules were also formulated to follow during the programs. A committee oversees the testing process in Arizona.

3.7.2.2 Connected Vehicles

3.7.2.2.1 Vision. We spoke to Mr. Faisal Saleem, ITS branch manager of Maricopa County. Mr. Faisal had a key point about CV development: If the rulemaking happens, by 2023, every new vehicle will have DSRC technology installed in it. Because of this rulemaking, by 2025, 10-15% of all vehicles will have this technology. The gradual introduction of DSRC vehicles guarantees that CV technology will be introduced in an evolutionary manner.

3.7.2.2.2 Objectives. Arizona is committed to improving the safety and mobility of its road systems through incorporating CV technology.

3.7.2.2.3 Initiatives. In the areas of safety and mobility, numerous initiatives are being undertaken by Arizona Department of Transportation (ADOT). For the combined purposes of safety and mobility, ADOT is testing the implementation of traffic signal preemption for emergency vehicles. This can save lives and money through preventing damage attributed to delayed emergency vehicle arrival. From the standpoint of safety alone, work zone safety is being enhanced by using DSRC radios to alert drivers of whether they are approaching a worker. School zone safety is being enhanced through similar means. Also, for testing safety applications, a test bed has been constructed through a partnership with the University of Arizona and ADOT.

3.7.2.2.4 Planning. Faisal mentioned that the Anthem test bed would eventually incorporate test subjects into the experiments. This will represent an increase in the testing operation's scale- a noteworthy step towards deployment.

3.7.2.2.5 Challenges. A national challenge pertaining to AVs is the competition presented by their CV counterparts. CV technology is more proven, lower cost, and easier to implement than AV technology. Hence, AV development will be more difficult to progress. Also from a national standpoint, the uncertainty about AV/CV technology and the associated rulemaking are discouraging investment into the field. This must be rectified to standardize the technology and accelerate its development.

3.7.2.2.6 Opportunities. Faisal indicated officials in industry are well aware of the potential interoperability issues. They are eager to collaborate to address this problem, opening the opportunity for AV/CV deployment on a large scale.

Takeaways for INDOT:

- MCDOT recommends agencies focus on short term planning.
  - This is because numerous aspects of the technology are changing at a rapid pace, including the rulemaking.
  - Hence, strategically speaking, it is not prudent to plan for the distant future if the next ten years of the technology are unpredictable.

3.8 Region 10

3.8.1 Oregon

3.8.1.1 Connected Vehicles. We interviewed Andrew Dick and Galen McGill from Oregon Department of Transportation (ODOT).

3.8.1.1.1 Vision. ODOT believes AV/CV technology is going to be developed and deployed in the future and will have significant impacts in terms of safety and mobility. However, ODOT is uncertain about the technology's timeline of development, and whetherit will employ the 5G, 4G, or DSRC means of communication.

3.8.1.1.2 Objectives. ODOT seeks to achieve connected and automated deployment in large numbers on its road systems.

3.8.1.1.3 Initiatives. ODOT is currently using CV technology to convey information about weather, road hazards, and road construction locations to consumer vehicles, through what is known as the trip-check traveler information portal. This improves driver awareness. In addition, ODOT has instituted a voluntary process through which OEMs can apply for permits to test AV technology or applications. Thus, ODOT is facilitating the process for OEMs to test their vehicles on public roads. Additionally, ODOT is exploring AV/CV traffic control. Lastly, ODOT has participated in the writing of a national manual on uniform traffic control devices

3.8.1.1.4 Planning. ODOT has plans to explore priority signals for transit and emergency vehicles.

3.8.1.1.5 Challenges. ODOT must consider how to deploy AV/CV technology, as there are numerous options for doing so. ODOT has to ensure the infrastructure is in place to support AV/CVs and that the technology can succeed if it is developed properly.

3.8.1.1.6 Opportunities. ODOT has a regional opportunity to put RSEs at intersections across Oregon to utilize traffic signal system applications. The installation of RSEs depends on the application that state DOTs intend to test. There is no need to have a separate department to do this, as efforts are the extension of what ODOT is already doing.

Takeaways for INDOT:

- ODOT recommends that INDOT adopt a similar voluntary notification process to facilitate AV/CV testing by OEMs.

4. FUTURE DIRECTIONS FOR INDOT

4.1 Roadmap

In order to integrate AV/CVs into the operational framework of INDOT, a roadmap for the deployment of connected and autonomous vehicles will go a long way in achieving specific goals, which would culminate, into INDOT achieving its final objectives. The roadmap for INDOT has been divided into short-term, medium-term, and long-term objectives to incorporate AV/CVs on Indiana's roadways. Figure 4.1 is the AV/CV roadmap for INDOT.

Short-Term Goals

- INDOT should reevaluate the infrastructure investment plans, which are associated with capacity expansion or the implementation of ITS, given that AV/CV deployment will increase the roadway capacity.
- INDOT can join the V2I pooled fund as well as Smart Belt Coalition. These coalitions will be critical platforms for exchange of technical knowhow and results from AV/CV testing.
- INDOT should join the "INRIX AV Road Rules" project as a supporting partner to aid in and understand digitization of maps critical to the deployment of highly autonomous vehicles (see section 4.2.5).
- The agency should scrutinize agency goals and identify areas where connected technology will yield more benefits.
- It is important to determine particular issues in the areas that need solutions.
- Finally, INDOT should design applications that will concentrate on solving the imminent issues.

Medium-Term Goals

- It will be vital to create a committed AV/CV team to spearhead the deployment process.
- INDOT will need to standardize and enhance the visibility of signs on its roads. Lane markings should be visible all over the state. Clarity in pavement markings and signage is critical for the smooth deployment of AV/CVs.
- Testing is vital to evaluate the safety levels and impact of the vehicles on users and the environment.
- Another important goal is to identify regions for installing the RSUs in addition to upgrading and integrating DSRC in controlling signals at designated regions.
- INDOT will need to create in-house expertise by collaborating with academic institutions like Purdue University. Institutions perform research and development activities, which INDOT can benefit from. Therefore, liaising with them during the implementation of the roadmap is paramount in gaining theoretical and practical knowledge.
- Lastly, Indiana should deploy the CAVs in a staged manner to make sure issues are detected on time. The first step should be the deployment in the main locations.

Long-Term Goals

- A key long-term goal will be to identify the available funding options that will enable the expanded deployment of DSRC across Indiana. Often, projects are derailed by the lack of funds. At times, poor management or the lack of identifying sources of funds before starting a project leads to the halting of the same before completion and hence affecting other projects and processes. Therefore, INDOT has to plan for the sources of funds for the successful deployment.

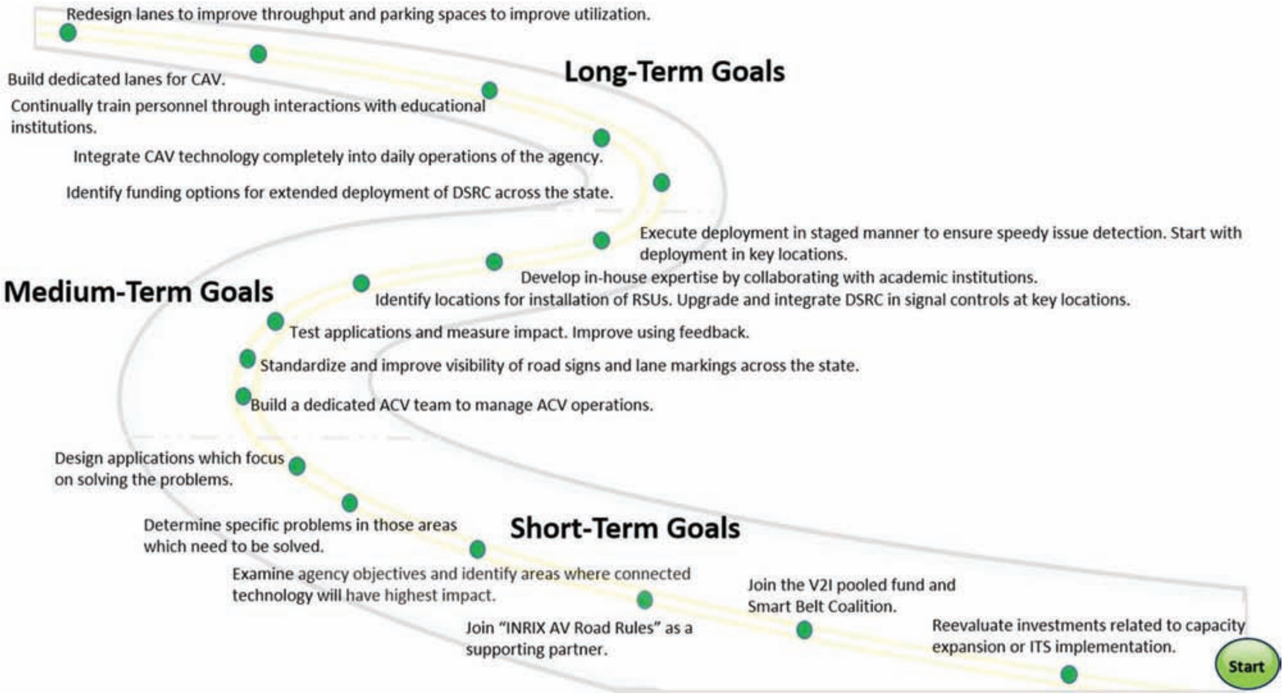


Figure 4.1 Roadmap for Indiana for AV/CV initiatives.

- INDOT should also make CAV technology part of its transport operations. As previously described, using the technology will improve safety and mobility.
- INDOT will need to focus on education, and outreach among all stakeholders to build synergy and cooperation.
- The parking spaces should also be restructured to cater to the new type of demand for parking. It is possible that AVs will need parking space for less amount of time as they will be completing trips for multiple individuals. At the same time, the demand for CAVs will result in higher number of vehicles. Therefore, redesigning the parking will be paramount in the deployment of CAVs.
- INDOT will need to redesign its lanes, which will improve overall mobility.

4.2 Important Considerations

4.2.1 Effectiveness of AV Technology

Presently, AV technology is developing its performance. While exciting works have been conducted in advancing the technology forward in recent years, AV technology is not ready for deployment. This assessment is supported by data from stakeholders such as Uber (Bhuiyan, 2017). AV technology's advanced features are offset by flaws in their handling of environmental factors, such as police or emergency vehicle intervention and the weather (Lowy, 2016). These current shortfalls of autonomous vehicle technology will reduce consumer confidence in AVs and lead to unsettled drivers.

Uber has been conducting extensive work into evaluating the performance of AVs on roads across America. Uber has been testing AV prototypes in California, Arizona, and Pennsylvania (Bhuiyan, 2017). Uber's AVs have steadily improved concerning the number of miles driven autonomously on a weekly basis. For instance, this number increased from approximately 5000 miles during the week of January 4, 2017 to approximately 20,000 miles during the week of March 8, 2017 (Bhuiyan, 2017). This testing primarily occurred in Pittsburgh, Pennsylvania. Despite Uber's AVs seeing an increase in the total number of autonomously driven miles, the frequency at which humans, who ride in Uber's AVs to monitor their performance, must take over is still exhibiting a lack of progress. In fact, the frequency at which human intervention occurs has increased since January. Driver intervention is necessary during times that the AVs fail to react properly to scenarios on the road.

Uber measures the performance of its autonomous vehicles with a variety of metrics (Bhuiyan, 2017). These metrics are the average number of miles a car drives itself before a driver takes control (for any reason); the average number of miles before a driver has to intervene to avoid causing over $5,000 in harm to pedestrians or property; and the average number of miles before poor driving experiences, such as hard braking and jerky motions (Bhuiyan, 2017). During the week of March 8, 2017, Uber's data demonstrated the lack of readiness of AV technology. For its 43 active cars nationwide, an average of a mere .8 miles elapsed between driver interventions for any reason. This statistic is denoted by Uber as the number of miles per intervention (Bhuiyan, 2017). The reasons behind these interventions varied. Among those cited were unclear lane markings and inclement weather. The miles per intervention in March actually represented a decline from January. Rarely, if ever, has Uber recorded this statistic exceeding one mile.

Uber's statistics suggest that AVs confined to a particular region will perform poorly and fail to meet the lofty expectations held by many. Uber indicates that introducing cars to new locations and new routes has a strong correlation with a decline in AV performance (Bhuiyan, 2017). Obviously, learning from environmental cues and adapting to a diverse array of scenarios is an imperative feature for AVs to have. It is impossible to program every single scenario an AV will encounter into the AV. This aspect of AV technology, intelligent learning, is critical to the technology's performance and must be improved before AVs are introduced onto road systems. Other reasons for poor AV performance, as indicated by Missy Cummings, director of Duke University's robotics program, include an inability to handle bad weather such as standing water, downpours, and snow (Lowy, 2016). Furthermore, AVs cannot handle external intervening factors from figures of authority, such as yielding to emergency vehicles and following the directions of a police officer.

While Uber's statistics portray recent AV improvement as being primarily stagnant, progress has been made in certain areas. For example, the number of miles between "critical interventions," when the driver has to intervene to avoid causing over $5000 in pedestrian or property damage, has recently seen a dramatic improvement. During the week of March 8, 2017, Uber's vehicles drove an average of 200 miles between critical interventions. This contrasts with January's figure of 125 miles between critical interventions. With the exception of minor weekly aberrations, the general trend in Uber's AV fleet has been an increase in the miles driven autonomously before critical interventions by human are required.

Uber's data agrees with a general trend seen in public polling. A 2017 AAA survey indicated 78% of drivers in the United States are afraid to ride in an autonomous vehicle (Business Facilities, 2017). Furthermore, 54% of drivers would feel less safe sharing a road with an AV. Data indicating the performance of AVs and public unwillingness to trust the technology are not deterring automakers from lobbying for its introduction. Ford, Google, Uber, Lyft, and Volvo recently formed a group, the Self-Driving Coalition for Safer Streets, to establish a clear set of national standards for AVs (Business Facilities, 2017). As early as 2019, many automakers are inclined to put AVs on the market. This comes in spite of the fact that the nation's infrastructure needs over $2 trillion in repairs, many of which relate to matters critical to AV functionality, such as establishing and maintaining clear lane markings and standardizing signs.

It is a little too optimistic on the part of manufacturers to keep such inflated targets. AV manufacturers are motivated by the fact that 94% of traffic deaths involve human error, which can be reduced through removing the driver altogether. However, the automakers must realize that, based on data from innovators in the field, such as Uber, AVs are not ready to be deployed with their current level of advancements. Doing so would be unsafe to AV passengers and other vehicles. It would also accomplish little in improving the driver experiences, as unsettling vehicle behavior was common in Uber's testing (Bhuiyan, 2017).

4.2.2 Fundamentals of CAV Functions

CAVs discern pavement markings, identify objects, and initiate steering and braking through employing a variety of sensors. Each sensor performs numerous functions. These respective functions are allocated by the CAV manufacturer depending on the capabilities of the sensor. The primary sensors employed in CAVs are RADAR, camera, and LIDAR systems (NXP, 2017). It must be stressed that overlap exists in the functions performed by each sensor. For example, cameras act as a supplement to RADAR in performing Adaptive Cruise Control (ACC) functions. This is to give a CAV redundancy in sensors and increase safety.

CAVs discern pavement markings with either camera or LIDAR sensors. The predominant sensor employed for pavement marking identification is the camera. For example, General Motors is employing technology from Mobileye, an Israeli firm, to employ cameras to detect road markings, signs, and traffic lights (Davies, 2016). GM plans to go beyond using Mobileye's technology on a basis individualized to each vehicle. Rather than simply identify the lane markings of each road and discard the data after it is used, GM plans to employ data from all its vehicles equipped with the technology to create a comprehensive database of the American road network, which will allow an autonomous vehicle to detect its location within an accuracy of roughly 10 centimeters (Davies, 2016). The most significant advantage of using cameras for CAV detection of pavement markings is its cost. It is much cheaper to purchase a front facing camera than RADAR or LIDAR systems (Dwivedi, 2017). For AV manufacturers, this will make their vehicles more affordable and marketable to everyday consumers, which will increase market saturation and the effectiveness of their AVs as a result.

Cameras are employed to identify lane markings through a simple process. First, the image of the road at a particular moment is processed by an onboard computer, which removes distortions (Dwivedi, 2017). Next, the image is transformed into a binary image. The binary image is black and white. With lanes being a distinct white due to contrast, their position relative to the front of the vehicle is identified during this phase. This binary image is then transformed into a bird's eye view image through manipulating its perspective. The bird's eye image allows the vehicle to identify lane curvature, completing its analysis of the pavement markings in front of it (Dwivedi, 2017). The fully identified lanes are plotted back onto the AV's image of the road, which clearly marks the lane area for the vehicle and enables accurate navigation. The low cost of cameras also makes them applicable to other simple CAV operations in identifying object in the environment (NXP, 2017). These operations include parking assist, traffic sign recognition, and forward collision warning. More advanced processes require either LIDAR or RADAR technologies.

As an alternative to cameras, LIDAR-based lane marking detection and mapping features can be employed to produce a similar result to the pavement marking identification process by camera (Kammel & Pitzer, 2008). LIDAR systems use numerous lasers, the exact number of which depends on the system employed, to create a 360-degree field of view around the vehicle. Millions of laser points per second are produced, providing an extremely high-resolution 3D map of the vehicle's surroundings (Kammel & Pitzer, 2008). Lane markings are identified by LIDAR systems due to their retroreflectivity. They offer significant contrast to other surrounding features in the LIDAR-generated point cloud. Due to the intense saturation of LIDAR laser points, LIDAR technology is capable of producing lane-marking maps of higher accuracy than those generated by its camera counterparts (Kammel & Pitzer, 2008). However, it must be noted that LIDAR technology is far more expensive, making it less applicable to AVs intended for consumer markets. In addition, after a certain point, additional accuracy in lane marking mapping is unnecessary. Cameras provide adequate amounts of detail for their intended application of mapping pavement markings at far less cost than LIDAR systems, making them more appealing to automakers at the present (Dwivedi, 2017).

Other than lane markings, RADAR and LIDAR systems are predominantly utilized to identify objects in a CAV's environment (NXP, 2017). RADAR has several classifications: Short Range Radar has up to a 30 meter range, Medium Range Radar has a 30 to 80 meter range, and Long Range Radar has a range of over 80 meters. Since RADAR is less computationally demanding than LIDAR systems and can function in almost all environmental conditions, it is the industry-preferred sensor for applications requiring rapid sensory input and feedback (NXP, 2017). These are Adaptive Cruise Control and highway Automatic Emergency Braking Systems. However, RADAR technology is limited in its coverage in certain scenarios. An example of this is a car cutting in front of a RADAR-equipped vehicle. RADAR is also poor at detecting objects with discrete profiles, such as motorcycles (NXP, 2017). Because of this, cameras often are paired with RADAR systems to provide additional context to a vehicle's surroundings, improving CAV awareness.

TABLE 4.1
Performance of the Sensors across Key Performance Metrics in Autonomous Vehicles

		AV			CV	CAV
Performance aspect	**Human**	**Radar**	**Lidar**	**Camera**	**DSRC**	**CV+AV**
Object detection	Good	Good	Good	Fair	n/a	Good
Object classification	Good	Poor	Fair	Good	n/a	Good
Distance estimation	Fair	Good	Good	Fair	Good	Good
Edge detection	Good	Poor	Good	Good	n/a	Good
Lane tracking	Good	Poor	Poor	Good	n/a	Good
Visibility range	Good	Good	Fair	Fair	Good	Good
Poor weather performance	Fair	Good	Fair	Poor	Good	Good
Dark or low illumination performance	Poor	Good	Good	Fair	n/a	Good
Ability to communicate with other traffic and infrastructure	Poor	n/a	n/a	n/a	Good	Good

Source: Schoettle (2017).

LIDAR sensors offer a distinct advantage that makes them a great asset to enhancing a CAV's ability to detect objects in its surrounding environment. This advantage is LIDAR's ability to provide a 360-degree 3D view of obstacles in a vehicle's surroundings up to hundreds of feet away (NXP, 2017). LIDAR technology accomplishes this through saturating the vehicle's periphery with millions of laser points per second (Kammel & Pitzer, 2008). Ideally, LIDAR would be employed in all CAVs to provide rich depictions of the environment. However, the drawback with LIDAR, the cost of each system, is preventing their widespread introduction from occurring (NXP, 2017). While cost reductions have occurred in recent years, the most widely implemented models for CAVs remain significantly more expensive than their RADAR and camera counterparts. In fact, some LIDAR systems cost more than the CAV they are intended to support (NXP, 2017). As a result, LIDAR systems are not applicable to all consumer CAVs, as they would make models unaffordable for a large portion of potential buyers.

From a high-level, CAVs execute decision-making, such as steering and braking, through a straightforward process. A recent guide for AV policymakers, published by RAND Corporation, provides a general outline of the AV decision-making process (Anderson et al., 2016). This process is depicted as the same "sense-plan-act" design that is foundational for numerous robotic systems (Anderson et al., 2016). Initially, sensors, such as the LIDAR, camera, and RADAR systems outlined previously, will gather raw environmental data that depicts the vehicle's relationship with its surroundings. Software integrated with onboard computers will interpret this sensory data to determine a corresponding action. An example of this is lane-marking imagery being processed to dictate CAV lane centering. At any moment, numerous images and quantities are being processed individually and in relation with each other. The result of this processing is determined to be the optimal vehicle behavior for any given situation (Anderson et al., 2016). It must be noted that this processing must occur within a fraction of a second, as a vehicle's surroundings will be changing at a rapid rate, requiring almost immediate reactions.

The ideal action determined by the CAV's computers will be converted by software into commands executable by the vehicle's control system. For example, if a red light were detected, a braking command would be issued to the vehicle's braking system. It must be noted that numerous "sense-plan-act" loops are operating concurrently on CAVs at varying levels of frequency, due to the multitude of processes required by a vehicle's operation. One loop may be responsible for handling vehicle braking, while another may be responsible for initiating and executing lane changes. Furthermore, some loops only reach the action stage in unique situations, such as reacting to police cars or emergency vehicles.

In a study done by Sustainable Worldwide Transportation at the University of Michigan, which compared the sensors capability to detect and classify object among other functions it was found that these sensors preform quite well as compared to humans in most areas and perform better than humans in poor illumination and bad weather conditions. Table 4.1 is a table from the report by Sustainable Worldwide Transportation (Schoettle, 2017).

4.2.3 Required Level of Service for AV/CV Operations

The introduction of autonomous vehicles onto road systems will require supporting infrastructure to facilitate their proper application. To function, AVs will be required to recognize their environment and stay on the road. Lane markings are necessary to guide AVs and keep then in the correct lane. Road signs are necessary to give AVs information about speed guidelines, work zones, and other key situational details. Hence, enhanced retroreflectivity levels for road signs and lane markings are critical for AV functionality. The retroreflectivity of road signs and lane markings must be maintained at the greatest possible levels. Since there are no widespread standards for lane marking and road sign retroreflectivity, INDOT should model its maintenance standards for these infrastructure components after the efforts of other state DOTs and the Findings of past research conducted.

The North Carolina Department of Transportation is currently developing minimum retroreflectivity levels for its roads, defining acceptable performance requirements to enable AV functionality (Lacy, 2017). These standards will be based on testing using LIDAR and camera-equipped AVs. The testing will study center, lane, and edge lines. Tests will be conducted in wet, dry, day, and night conditions. Various types of markings will be evaluated. Current NCDOT standards exist for retroreflectivity of both signs and lane markings (Lacy, 2017). For thermoplastic material, the minimum levels range from 250 to 375 millicandelas, depending on the type of lane marking or sign. For paint, the minimum levels range from 200 to 225 millicandelas, which is also dependent on the type of lane marking or sign (Lacy, 2017). Whether these standards will be made more stringent will depend on the results of NCDOT's testing. Regardless of the testing's results, it is known by NCDOT that additional funds will be required to pave secondary roads and potentially improve markings on currently paved roads. INDOT should not wait on other state DOTs and transportation authorities to develop performance guidelines for lane markings and signs. Instead, the agency should conduct testing similar to that of NCDOT to ensure its infrastructure is prepared for the advent of AVs.

Potential performance requirements for pavement markings and signs were evaluated by Potters Industries (Davies, n.d.). Potters specifically evaluated the impact of pavement markings of various levels of retroreflectivity on the performance of AVs using a machine vision system. Potters' Findings can also be applied to signs, as materials that are easily recognized as lane markings will also be recognized as signs. During the day, luminance contrast ratio, not retroreflectivity, was found to be the most important factor for machine vision performance. White panels with a 6.76 luminance contrast ratio had were found by Potters to be, by far, the most effective. From 24 to 56 feet in front of the vehicle, detection of the markings was of the highest confidence (Davies, n.d.). The next best performing markings were light gray panels with a 3.81 luminance contrast ratio, which had a high certainty of detection between 40 and 54 feet in front of the vehicle- a significant decrease from the white panels. As long as markings were present on the road, in daylight clear conditions, the retroreflectivity of the markings had little impact on the performance of machine vision; markings of retroreflectivity levels ranging from 40 mcd to 900 mcd were all detected with complete certainty. On the other hand, at night, marking retroreflectivity was found to be the most important factor influencing their detection by vehicles (Davies, n.d.). The machine vision of the 900 mcd panels was the most reliable, as their detection was a near certainty between 27 and 57 feet in front of the vehicle. Marking contrast ratio was not a factor at night, as various contrast ratios yielded the same results. A similar study is underway as task six of NCHRP 20-102 (refer section 2.6.7.2) which is investigating the impacts of performance characteristics of pavement markings on the ability of machine vision systems to identify them (NCHRP, 2018). INDOT should consider the Findings of both the studies when developing its own testing procedures and standards for signs and pavement markings.

4.2.4 Utilization of CAV Data for INDOT's Maintenance Needs

INDOT will be able to use data from CAV applications to determine the quality of the road surface, the clarity of the signage and road markings, the weather conditions on the road in order to provide active infrastructure maintenance and improve ridership experience.

1) Road profiling is a crucial practice for the transportation agencies. Many DOTs are interested in measuring the longitudinal profile of roads for maintenance needs. INDOT will be able to utilize data from CAV applications, which measure the longitudinal profiles of road roughness. One of the main measures of road roughness is the International Roughness Index. This measure is calculated using a mathematical model which outputs roughness index with units of slope (in/mi, m/km, etc.). It was introduced by World Bank in 1986 and since then has become the most commonly used worldwide measure for evaluating and managing road systems. The longitudinal road roughness can be measured using multiple methodologies like incorporation laser sensors or also using other CAV application to measure vertical movements of the vehicles for a unit distance covered by the vehicle. Additionally, smartphone applications have been introduced recently that use user data to analyze the road condition. Point to note is that for laser-based sensors the measuring tasks are challenging for most lasers in spite the fact they have higher accuracy because road surfaces present many dynamically changing targets including tarmac, concrete, yellow striping, white striping, etc. Therefore, there are special lasers to maintain a consistent sampling rate over varying target.
2) Autonomous vehicle systems assume that line markings exist, are clear and, more importantly, and are visibly distinct. However, the US Department of Transportation estimates that 65% of its roads are in poor condition, meaning that autonomous vehicles will have considerable difficulty driving on them. Poor markings and uneven signage are forcing automakers to develop more sophisticated sensors and maps to compensate. In addition, vehicle-to-infrastructure (V2I) applications can be used to inform the vehicle about the road markings and signage condition from the infrastructure, which gathers local or global information. CAV applications can be developed which use the LIDAR sensors to measure the level of clarity of the road markings and signage and that data can be used to understand the quality of road infrastructure and the maintenance requirements.
3) In a typical year, there are 1.2 million weather-related vehicle crashes in the U.S., leading to 445,303 injuries and over 5,897 fatalities. Adverse weather and the associated poor roadway conditions are also responsible for 554 million vehicle-hours of delay per year in the U.S., with associated economic costs reaching into the billions of dollars. A possible solution for mitigating the adverse

> impacts of weather on the transportation system is to build CAV applications, which measure the road weather conditions using which road maintenance operators can act accordingly. One of the effective application to look at road weather conditions is MDSS, which provides clear, actionable information about weather and roadway conditions so DOTs can make confident and effective decisions on deployment, materials, and tactics when responding to weather events. The MDSS software integrates current and forecast atmospheric weather and pavement condition data with agency snow and ice policies for a comprehensive maintenance strategy.

The above applications can be used by INDOT to make their maintenance efforts more effective and cost effective.

4.2.5 Interaction between Highway Agencies and Industry over Infrastructural Requirements

An estimated 65% of U.S. roads are in poor condition, according to the U.S. Department of Transportation. Not up to mark infrastructure has become a roadblock to the development of self-driving cars, vexing engineers and adding time and cost. Poor markings and uneven signage on the 3 million miles of paved roads in the United States are forcing automakers to develop more sophisticated sensors and maps to compensate, industry executives say.

In this context, cooperation between the industry and the agencies can lead to a fruitful advancement of CAVs on the roadways. Some of the immediate improvements the agencies should focus on is the basic infrastructure improvements such as improvements in road markings and signage. While discussing with the automakers, they suggested that the transportation agencies could provide the automakers with highly detailed road maps. This detailed map of roads will help the automakers along with the sensor technology and machine learning tools to make the cars more reliable and robust. Therefore, some assistance from the agencies will go a long way into the efficient and smooth operations of autonomous cars. In fact, INRIX (a company specializing in connected car services and transportation analytics) is developing a platform named "INRIX AV Road Rules" that allows cities to digitize pavement markings, signage and other relevant information about local rules (INRIX, 2018). They are inviting partnerships from road authorities as well, and we recommend that INDOT join the project. It is an opportunity to understand the type and format of maps that are required for a smooth deployment of highly autonomous vehicles on roads.

4.2.6 Cloud as a Basis for V2V and V2I Communication

The convergence of mobile internet and Internet of Things will result in the inevitable emergence of V2V and V2I communication via cloud. It will involve the combination of information communication, energy conservation, and safety.

Cloud based work in autonomous vehicles has already been researched in Japan and Europe. In Europe, Ericsson is working on a 5G project for connected vehicles that could lead the way for cloud based connected applications.

Cloud based applications will feature dynamic mobile communication systems that communicate between vehicles and public networks using V2V (vehicle-to-vehicle) and V2I (vehicle-to-infrastructure) interactions. It will enable information sharing and the gathering of information on vehicles, roads and their surroundings. Moreover, it will involve the processing, computing, sharing and secure release of information onto information platforms. Based on this data, the systems can effectively guide and supervise vehicles, and provide abundant multimedia and mobile Internet application services.

Viewed from the network perspective, the cloud based CAV applications will comprise of a three-level "Client-Connection-Cloud" system. The client system is a vehicle's intelligent sensor, which gathers vehicular intelligence and detects driving status and environment.

Connection system layer addresses V2V and V2I (vehicle-to-Internet) interconnectivity to realize communication and roaming between vehicular ad-hoc networks (VANETs) and other heterogeneous networks.

The cloud-based vehicle operation information platform will covers ITS, logistics, cargo/passenger transport making it a repository of highly valuable vehicular data. Additionally, cloud-based functions such as verification, interaction in real-time and data storage will be implemented.

4.2.7 Lane Positioning by AV System in Severe Weather or Poor Road Infrastructure Conditions

In cases where the sensory units of autonomous vehicle such as camera are unable to detect the lane markings, the autonomous vehicles can then utilize the data from GPS and inertial measurement unit (IMU) to keep itself on track. For this, the autonomous vehicle would require high-resolution maps of the terrain where it is operating as an input. Afterward, the position or location data from GPS and IMU can be matched to the maps to keep the vehicle in the lane. Further, an autonomous vehicle can also utilize the data fusion technique to determine its path based on the previous trajectories used on the same road by the other vehicles. The historical data combined with the GPS and IMU measurements can also be utilized to position the vehicle (Lambert, 2016).

4.2.8 Economic Impact of CAV Technology

A study by Clements and Kockelman (2017) looked at the economic effects of automated vehicles.

Industry-Wide Annual Economic Effects (Clements & Kockelman, 2017). Table 4.2 reports the change induced by CAVs in various industries. Insurance industry may

TABLE 4.2
Industry Wide Annual Economic Effects

Industry	Size of industry (billions)	Dollar change in industry (billions)	Percent change in industry	$/capita
Insurance	$180	-$108	-60	$339
Freight transportation	$604	+$100	+17	$313
Automotive	$570	+$42	+7	$132
Personal transportation	$86	-$27	-31	$83
Oil and gas	$284	+$14	+5	$44
Medical	$1067	-$12	-1	$36
Electronics and software technology	$203	+$26	+13	$83
Traffic police	$10	-$5	-50	$16

Source: Clements and Kockelman (2017).

have to face a possible restructuring of their business due to the enhanced safety features of CAVs. Trucking and ground shipping industry can experience a significant boost from the autonomous fleet. For instance, truck platooning and reduced truck collisions would allow efficient operations. Further economic gains can be resulted from the elimination of wages of truck drivers. In the personal transportation space, CAVs will likely introduce on-demand services for short commutes. This way, public transportation and taxi industries are likely to be affected and they may lose revenue.

Economy-Wide Annual Economic Effects (Clements & Kockelman, 2017). CAVs are likely to increase the capacity of infrastructure because of improvement in the efficacy of operation. An estimated $488 billion/year can be saved through reduction in injuries and deaths from collisions. Since driver is no longer needed, he/she can utilize that time for other works thus bringing an increase in productivity amounting to $448 billion/year. Economy wide impacts are this valued at $936 billion/year as shown in Table 4.3 (Clements & Kockelman, 2017).

Impact on Jobs due to the Advent of Autonomous Vehicles (Beede et al., 2017). As of 2015, there were 15.5 million individuals in the US whose employment can be impacted by autonomous vehicles. The U.S. Department of Commerce Economics and Statistics Administration, Office of the Chief Economist did a study on the impact of autonomous vehicles on employment. In the study, they divided occupations into “motor vehicle operators” and “other on-the-job drivers.”

Motor vehicle operators transport people and goods, which is their primary activity. As of 2015, 3.8 million individuals were performing these jobs. The demographic of these individuals was mainly male, older, less educated, and paid less than the typical worker. Motor vehicle operator jobs are mostly concentrated in the transportation and warehousing sector. The impact of autonomous vehicles will negatively affect these individuals.

The other category of individuals who are classified as “Other on-the-job drivers” employ motor vehicles to supplement their work requirements like firefighters, plumber, house repair, construction workers, medical emergencies etc. These types of jobs constitute 11.7 million workers as of 2015. For these individual autonomous vehicles will help in increasing productivity and improve working conditions.

TABLE 4.3
Economy Wide Annual Economic Effects

Economic type of savings	Dollar change in industry (billions)	$/capita
Productivity	$448	$1,404
Collisions	$488	$1,530
Economy wide total	$936	$2,934

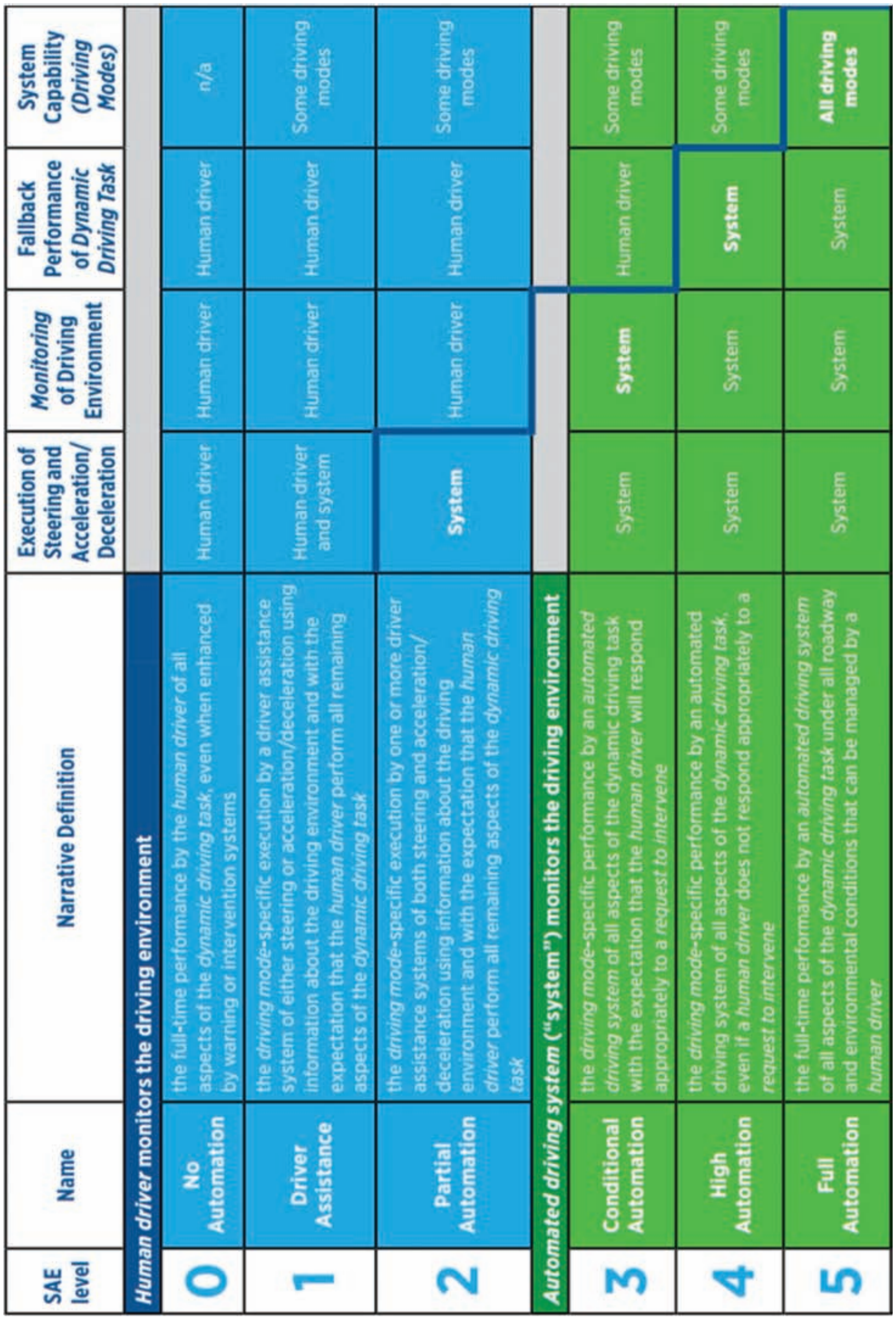
Source: Clements and Kockelman (2017).

4.2.9 Industry’s Timeframe for the Deployment of Level 4 and Level 5 Vehicles

Figure 4.2 illustrates the difference between Level 4 and Level 5 (SAE). Key terms such as dynamic driving task, driving mode, and request to intervene are defined by SAE as follows.

- Dynamic driving task includes the operational (steering, braking, accelerating, monitoring the vehicle and roadway) and tactical (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the strategic (determining destinations and waypoints) aspect of the driving task.
- Driving mode is a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high-speed cruising, low speed traffic jam, closed-campus operations, etc.).
- Request to intervene is notification by the automated driving system to a human driver that s/he should promptly begin or resume performance of the dynamic driving task.

Level 4 is a car that can drive itself almost all the time without any driving need but it may not be operable autonomously unmapped areas or during severe weather. In a way, self-driving is limited to certain driving locations and environments. Level 5 will be fully autonomous in all conditions that can be managed by a human driver.



SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 4.2 SAE levels of automation (SAE International, 2014).

Industry Timeframe. Currently, connected vehicle saturation levels are increasing at a significant rate. There are roughly one billion vehicles on global roads today (McCarthy, 2015). Out of these billion vehicles, in 2013, approximately 23 million of them had connectivity features, meaning they were connected to the internet. The technology's increasingly prevalent introduction into new vehicle models is growing these numbers. IHS Automotive has estimated that 20% of the vehicles sold worldwide in 2015 were connected vehicles (McCarthy, 2015). This percentage will increase in subsequent years. The manufacturing of new connected vehicles is projected by IHS to increase their global numbers to approximately 152 million by 2020. Gartner, an American research firm, has estimated this 2020 figure to be even greater- roughly 250 million. Regardless of the exact number of CVs on global roads in 2020, it is clear that their numbers are increasing and require supporting infrastructure to enable their effective deployment and full utilization.

Ford is eyeing for a 2021 timeline to deploy Level 4 car with high automation as per their press release (Ford Motor Company, 2016). Honda is targeting 2025 for the introduction of the vehicles with Level 4 capabilities (Byford, 2017). Nissan, on the other hand, believes that their ProPilot system will be able to handle Level 4 capabilities by 2020 and they plan to deploy a number of autonomous taxi during the Tokyo Olympics (Byford, 2017). Renault-Nissan with their new partner Microsoft plans to release 10 different self-driving cars by 2020 for urban conditions and fully autonomous car by 2025 (Fagella, 2017). Volvo plans to have a fully autonomous car by 2021 for highway conditions (Fagella, 2017). Hyundai is targeting the fully autonomous cars for highway by 2020 and for urban conditions by 2030 (Fagella, 2017). Diamler expects the large-scale production of Level 4 and Level 5 autonomous vehicles between 2020 and 2025 (Fagella, 2017). BMW in collaboration with Intel and Mobileye is developing highly and fully autonomous cars and they are targeting for the 2021 timeline (Fagella, 2017). Elon Musk from Tesla, however, optimistically tweeted that by the end of 2017, Tesla would be able to drive from Los Angeles to New York without a human driver taking the control of the car (Fagella, 2017). At the moment, the industry is aiming for Level 4, which is limited to certain driving conditions, since the car still cannot operate in all possible conditions.

4.2.10 Forecasting the Market Penetration of CAVs

Bansal and Kockelman (2017) presented a forecast for the United States towards the adoption of connected and autonomous vehicle technologies. Their analysis is based on previous NHTSA automation levels instead of newly adopted SAE levels of automation. In SAE levels, NHTSA Level 4 is divided into two to distinguish between highly autonomous and fully autonomous car (SAE). The analysis accounts for public willingness to pay for certain technologies, effects of regulations (regarding adoption of electronic stability control and connectivity using DSRC or 5G) and technology pricing. Bansal and Kockelman (2017) presented eight scenarios to the public in surveys of over 1000 individuals across the United States. In these eight scenarios, features such as electronic stability control, lane centering, left-turn assist, cross traffic sensor, adaptive headlights, pedestrian detections, adaptive cruise control, blind spot monitoring, traffic sign recognition, emergency automatic braking and connectivity were grouped in to SAE Levels 1 and 2 of automation. Survey respondents indicated whether they were willing to pay for these technologies, as well as how much they were willing to pay to add them. Table 4.4 is included in this report from the work of Bansal and Kockelman (2017). In these tables, WTP refers to willingness to pay. The resulting public opinions were incorporated into modeling to directly take into account public acceptance of the technologies presented in the scenarios. The modeling forecasted Americans' long-term adoption of CAVs.

4.3 Conclusions

Numerous conclusions can be made from the work conducted by this project. First, it is evident from the surveys of various transportation authorities that a consensus exists pertaining to the advent of AV/CVs. The vast majority of individuals surveyed across the United States indicated AV/CVs would come about in an evolutionary manner. Also, from the surveys, the transportation authorities indicated a widespread preference for a DSRC mandate. This is because of DSRC's reliability and proven safety levels through achieving low latency during testing. However, DSRC's introduction is not a complete certainty. If the latency of 5G technology is improved, then the surveyed individuals expressed openness towards adopting the technology on connected vehicle platforms.

Furthermore, due to the critical nature of research and development in the AV/CV field, it is imperative that INDOT join pooled fund studies and the smart coalition. This would allow INDOT to acquire a diverse array of knowledge about AV/CV deployment, evolving standards, and the technology in general. INDOT would also have the opportunity to influence the technology's development if it elected to join the aforementioned organizations.

From the project's studies, it is abundantly clear AV/CVs have the capability to dramatically change how people drive, what they drive, and whether they drive at all. CVs can improve driver awareness to yield tremendous benefits to driver safety, mobility, and reduce the environmental impact of vehicles. The market penetration of AVs will yield similar benefits, potentially to a much larger degree through removing the driver and dramatically reducing the imperfections of human behavior. Therefore, INDOT should prioritize the preparation of its infrastructure networks for AV/CV technology. Means of preparation include installing clear lane markings, DSRC radios on traffic signals, and ensuring the standardization of road design and signage. Also INDOT should exercise caution in developing an AV/CV-ready infrastructure, as the technology's rapidly changing nature can quickly render changes previously deemed necessary obsolete.

This report also looks at the important considerations which public agencies like INDOT should find useful in section 4.2. These considerations throw light on the critical aspects of CAVs, including the evolution of the technology, forecasting of the AV/CV future, interaction between the industry and public agencies over infrastructure requirements, the required level of service needed for safe and efficient CAV operations, utilization of data retrieved from CAVs for agency maintenance needs, and future technological improvement using the cloud as a basis for V2X communication. The report concludes by providing an overview of the modeling framework to be utilized for part-II of the project.

TABLE 4.4
Forecasting the Market Penetration of CAVs

	Scenario 1: Constant WTP, 10% drop in tech prices, and no regulation							Scenario 2: No-zero-WTP, 10% tech price drop, and no regulation						
Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic stability control	24.3	25.3	33.2	43.3	52.7	58.2	63.8	24.3	32.3	43.8	61.2	76.7	83.2	92.9
Lane centering	4.4	8.3	18.9	31.0	40.8	48.8	56.8	4.4	8.6	20.2	33.5	45.9	55.2	68.8
Left-turn assist	3.8	9.9	20.1	32.4	41.8	50.3	58.1	3.8	10.4	21.8	35.1	47.2	65.6	80.2
Cross traffic sensor	10.9	12.9	22.6	35.1	45.1	52.6	60.3	10.9	13.8	25.9	41.1	53.7	66.0	82.8
Adaptive headlights	10.2	9.7	18.8	30.9	41.0	49.2	58.0	10.2	9.8	19.8	32.4	46.2	55.9	77.5
Pedestrian detection	3.7	10.6	21.7	34.5	44.1	52.6	59.8	3.7	11.2	24.1	38.2	50.3	69.1	82.8
Adaptive cruise control	13.3	14.9	24.1	35.2	44.7	52.2	59.8	13.3	16.2	27.0	40.1	53.4	62.2	76.1
Blind-spot monitoring	11.7	15.0	26.1	38.5	48.2	55.1	62.1	11.7	17.3	31.9	46.3	59.7	67.8	80.7
Traffic sign recognition	2.0	7.7	18.0	30.0	39.8	48.9	57.0	2.0	7.6	18.4	31.4	43.5	63.3	78.6
Emergency automatic braking	5.6	11.8	24.4	37.1	46.9	54.6	61.6	5.6	11.8	26.4	43.7	57.7	74.3	86.2
Connectivity	0	17.7	34.8	44.7	51.1	53.0	59.5	0	18.0	35.2	46.1	57.6	61.4	83.5
Self-parking valet	0	9.1	21.4	33.9	45.1	52.5	61.2	0	9.2	21.6	34.5	46.3	54.4	73.5
Level 3 automation	0	2.1	4.6	7.6	8.3	8.0	10.4	0	3.0	5.3	7.7	8.7	7.9	13.7
Level 4+5 automation	0	3.9	11.1	19.7	28.6	37.0	43.0	0	3.0	10.2	19.0	28.7	37.9	43.8
	Scenario 3: No-zero-WTP, 5% drop in tech prices, and regulations							Scenario 4: No-zero-WTP, 10% drop in tech prices, and regulations						
Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic stability control	24.3	88.9	98.6	99.8	100	100	100	24.3	89.1	98.4	99.9	100	100	100
Lane centering	4.4	6.1	12.0	19.7	27.1	33.1	40.7	4.4	8.5	19.9	33.0	45.5	53.9	66.5
Left-turn assist	3.8	7.9	14.2	21.3	28.1	35.1	42.5	3.8	10.0	21.8	35.0	46.5	60.6	75.1
Cross traffic sensor	10.9	11.7	16.8	22.9	31.9	39.1	47.4	10.9	13.7	25.4	39.8	52.2	62.2	76.8
Adaptive headlights	10.2	7.6	11.2	18.3	26.4	32.6	39.9	10.2	9.5	19.6	32.3	46.1	53.6	71.6
Pedestrian detection	3.7	8.3	15.0	23.2	30.7	38.3	45.5	3.7	10.7	24.0	37.5	49.7	63.4	77.1
Adaptive cruise control	13.3	13.2	18.4	25.7	33.2	39.2	46.5	13.3	16.5	28.1	39.7	53.0	60.4	73.4
Blind-spot monitoring	11.7	13.8	20.3	29.7	39.6	45.7	53.5	11.7	16.5	31.6	45.6	59.1	66.0	77.2
Traffic sign recognition	2.0	5.4	10.5	17.7	24.9	31.4	38.1	2.0	7.3	18.2	30.9	42.7	58.7	73.9
Emergency automatic braking	5.6	8.6	15.6	26.1	34.7	43.4	51.2	5.6	12.3	26.3	42.3	57.2	69.1	80.9
Connectivity	0	36.5	88.2	98.4	99.7	100	100	0	41.3	88.4	98.4	99.7	100	100
Self-parking valet	0	6.0	13.1	20.9	29.0	34.9	41.6	0	9.2	21.1	33.4	45.7	53.4	71.9
Level 3 automation	0	1.9	3.2	4.5	6.5	8.1	8.9	0	2.7	5.1	7.5	8.7	8.2	13.9
Level 4+5 automation	0	2.0	5.2	10.3	15.0	19.2	24.8	0	2.9	10.2	18.8	28.5	36.3	43.4
	Scenario 5: 5% rise in WTP, 5% drop in tech price, and regulations							Scenario 6: 5% rise in WTP, 10% drop in tech price, and regulations						
Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic stability control	24.3	89.1	98.3	99.9	100	100	100	24.3	88.7	98.2	99.9	100	100	100
Lane centering	4.4	8.5	21.1	33.5	43.5	53.1	59.8	4.4	10.3	26.8	44.5	56.5	81.4	92.9
Left-turn assist	3.8	10.3	22.0	35.0	44.4	59.2	71.5	3.8	11.9	27.8	44.8	66.2	88.1	96.3

TABLE 4.4
(Continued)

	Scenario 1: Constant WTP, 10% drop in tech prices, and no regulation							Scenario 2: No-zero-WTP, 10% tech price drop, and no regulation						
Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Cross traffic sensor	10.9	14.3	25.7	39.6	50.6	60.9	73.4	10.9	15.7	32.1	50.2	68.9	87.3	96.3
Adaptive headlights	10.2	10.0	20.5	32.3	43.4	53.0	67.1	10.2	11.0	26.4	44.5	63.4	84.8	95.4
Pedestrian detection	3.7	11.1	24.5	38.1	47.9	61.4	74.0	3.7	13.2	30.9	48.5	68.6	88.6	96.5
Adaptive cruise control	13.3	16.1	27.4	39.4	51.8	60.3	68.3	13.3	18.3	33.9	51.5	66.7	86.4	95.8
Blind-spot monitoring	11.7	17.5	30.8	44.6	57.5	66.3	73.6	11.7	17.8	37.7	57.3	71.6	88.4	96.3
Traffic sign recognition	2.0	7.1	19.0	30.7	41.4	56.5	70.0	2.0	8.6	24.5	41.0	63.8	87.3	96.2
Emergency automatic braking	5.6	11.6	26.4	42.4	54.6	67.3	77.8	5.6	14.1	34.2	55.0	73.3	91.0	97.2
Connectivity	0	39.1	89.3	98.5	99.8	100	100	0	40.5	88.8	98.2	99.7	100	100
Self-parking valet	0	8.6	21.8	34.0	44.4	52.4	67.1	0	10.2	26.9	44.2	64.5	85.6	96.5
Level 3 automation	0	2.3	5.3	8.1	8.5	8.3	8.2	0	2.1	6.1	8.4	8.5	28.6	16.3
Level 4+5 automation	0	3.3	10.8	19.0	27.2	35.9	43.2	0	4.7	15.1	27.2	38.3	45.7	70.7

	Scenario 7: 10% rise in WTP, 5% drop in tech price, and regulations							Scenario 8: 10% rise in WTP, 10% drop in tech price, and regulations						
Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic stability control	24.3	89.7	98.1	99.8	100	100	100	24.3	89.1	98.8	99.9	100	100	100
Lane centering	4.4	10.8	25.5	42.1	55.1	78.1	90.3	4.4	13.5	32.8	51.2	79.0	94.0	97.9
Left-turn assist	3.8	11.6	26.5	43.0	65.1	83.6	95.0	3.8	14.1	34.1	60.9	87.3	96.4	98.4
Cross traffic sensor	10.9	15.6	30.8	48.3	65.4	84.6	95.0	10.9	18.2	39.3	63.6	87.0	96.6	98.5
Adaptive headlights	10.2	11.4	25.0	42.3	58.5	81.3	92.5	10.2	13.4	32.8	55.8	81.4	95.5	98.2
Pedestrian detection	3.7	12.9	28.8	45.8	67.9	84.6	95.3	3.7	15.3	37.6	63.7	87.9	96.8	98.7
Adaptive cruise control	13.3	18.0	31.7	49.1	62.5	82.8	92.8	13.3	20.3	40.4	60.2	83.2	95.4	98.2
Blind-spot monitoring	11.7	18.5	35.6	54.6	67.7	85.4	94.0	11.7	20.5	45.5	66.4	85.9	96.3	98.6
Traffic sign recognition	2.0	9.0	23.2	39.0	62.0	82.6	94.9	2.0	10.9	30.0	57.9	86.4	96.4	98.4
Emergency automatic braking	5.6	13.9	32.9	52.1	72.4	88.0	96.4	5.6	16.6	41.5	68.4	90.0	97.3	98.9
Connectivity	0	41.8	89.1	98.3	99.7	100	100	0	41.3	89.4	99.0	99.9	100.0	100.0
Self-parking valet	0	10.5	25.5	41.6	57.6	82.4	92.9	0	12.6	32.9	54.6	80.3	96.0	99.4
Level 3 automation	0	2.5	5.9	8.3	8.2	26.5	25.5	0	3.5	6.0	7.7	27.7	11.6	2.9
Level 4+5 automation	0	4.7	13.8	25.5	36.4	44.3	59.7	0	5.5	19.4	33.8	44.2	74.7	87.2

Source: Bansal and Kockelman (2017).

PART 2

5. OUTLINE

5.1 Background

As Connected and Autonomous Vehicles (CAVs) bring in a massive transition (Cuneo, 2017) their mobility and safety impacts are not known completely. This is a strong motivation to understand how these new age automobiles would usher in notable improvements in passenger safety, fuel emission and traffic congestion (Fagnant & Kockelman, 2015; Greenblatt & Shaheen, 2015; Li & Kockelman, 2016; Talebpour & Mahamassani, 2016). Below we discuss a brief background of Autonomous and Connected Vehicles.

5.1.1 Autonomous Vehicles (AVS)

Autonomous Vehicles have been an increasingly promising idea in the last decade in the transportation sector. AVs are expected to bring a significant change in the automotive and transportation landscape. There have been significant development in this area not only from the industry but also from the regulatory point of view (Anderson et al., 2014). AVs automate a significant number of driving features with the help of multiple technologies and sensors (Zhang, 2010). At the same time, NHTSA, in order to regulate the new phenomena has published a guidance document, which also includes the definition of levels of autonomy (NHTSA, 2016a). These levels have been adopted from Society of Automotive engineers (SAE) (SAE International, 2016b). We will discuss the various level of SAE in the next chapter in more detail.

5.1.2 Connected Vehicles (CVS)

Along with autonomous vehicles, connected vehicles are also at the forefront of intelligent transportation systems. With rapid development in wireless technology, connected vehicles are closer to becoming a reality. Vehicle-to-everything (V2X) communication along with infrastructure-to-vehicle (I2V) and infrastructure-to-infrastructure (I2I) communication have the potential to enhance mobility and safety of roadway networks. While connectivity among vehicles and infrastructure has numerous applications, we investigate two particular applications—platooning and signal control—in chapter 7 and 8 respectively.

5.2 Scope

5.2.1 Part 2

Task 4: Develop a Framework to Evaluate the Mobility Impacts of AV/CV Environment. We will develop a modeling framework that will evaluate the congestion impacts due to AV/CV environment using the framework developed in task 3. The potential benefits in terms of overall reduction in congestion, the benefits of travel time reductions with different levels of AV/CV penetration will be modeled. The research team will use VISSIM and agent based modeling tools developed by Dr. Ukkusuri to evaluate the potential reduction in delays, increase in speeds on various corridors. Specific corridors will be tested based on the input of SAC members.

Task 5: Testing Impacts on Intersection Crashes and Signal Coordination Due to AV/CV Environment. The project will summarize the potential benefits to reducing intersection crashes due to different levels of automation in the AV/CV environment at various levels of AV/CV market penetration. Similarly, the research team will identify the changes that will potentially be needed in the context of traffic signal coordination. There have been studies that have shown that perhaps there will be no need for signals within an AV environment leading to autonomous intersections. The research team will document the changes that are expected in the context of signal timing, signal coordination, speed harmonization within both the AV and CV environments. Sample results based on the research studies of Dr. Ukkusuri will be presented to clearly demonstrate the necessary changes in intersection control.

Task 6: Strategic and Tactical Advice to INDOT for an AV/CV Future. Based on research done in tasks 1 through 5, the research team will provide a set of recommendations to INDOT to allow positioning for an AV/CV future. The strategies will include decisions related to (1) the timing of various investments for operational and planning changes that INDOT should conduct; (2) the need for a specific individual within the organization who has responsibility for AV/CV; (3) potentially establishing a working relationships with resources in the state or region with useful expertise, such as universities, UTCs, and industry; (4) identifying the need for outreach to state and local policymakers to familiarize and educate them regarding AV/CV; and (5) establishing an internal group made up of people across various stakeholders to develop a strategic plan for implementation.

Deliverable. A project report will be developed based on the Findings in Part 2 mainly related to how INDOT can prepare for assessing mobility impacts and intersection crashes. Once this part is completed, the research team will evaluate how to deploy the Findings and if new studies are needed to prepare for the AV/CV future.

5.3 Methodology for CAV Modeling and Impact Assessment

Figure 5.1 presents the modeling framework utilized in this project. The modeling was done using VISSIM as the platform, which was integrated, with External Driver Model API (EDM). VISSIM allows vehicle characteristics such as speed and acceleration behavior

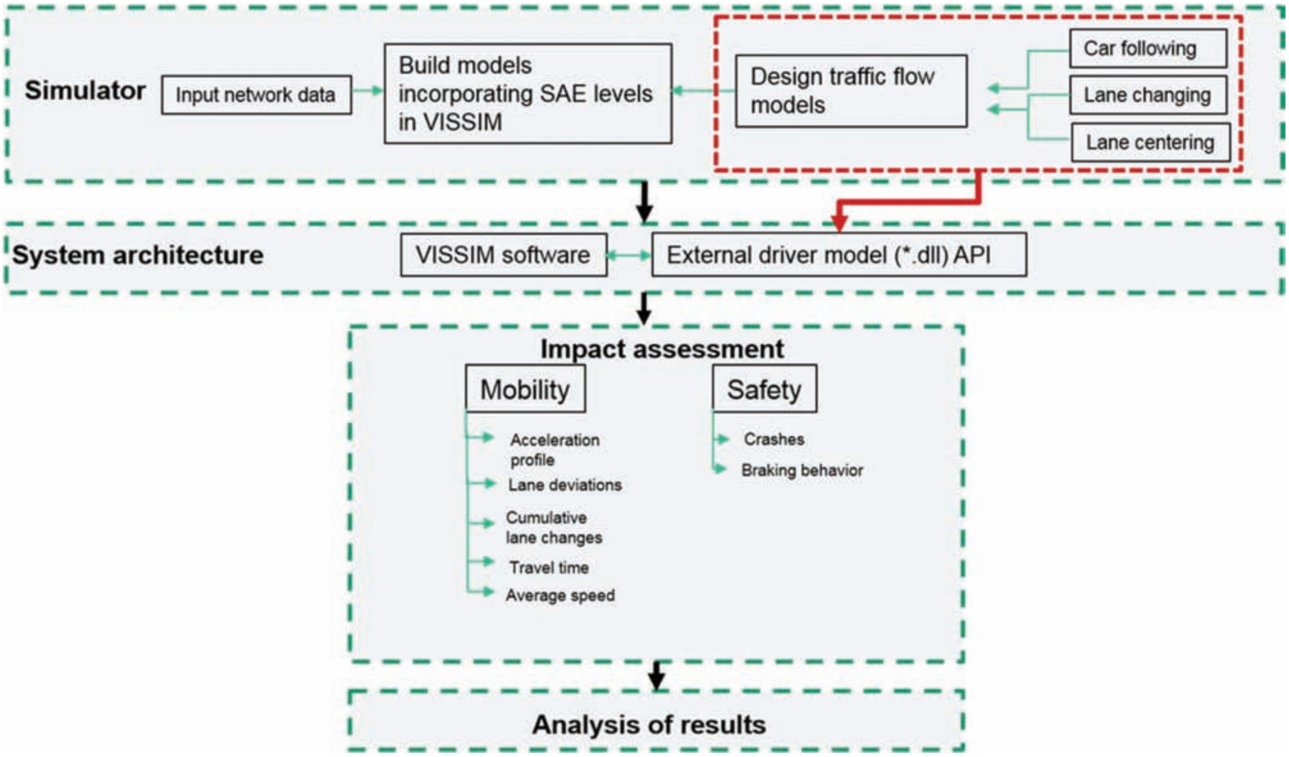


Figure 5.1 Framework for modeling AVs.

to be set according to the user's needs. In order to model the SAE levels, we designed/improved upon the existing models, which currently are limited to simulating human driver behavior. EDM is used to develop car-following models to represent different levels of automation (SAE). The driver behavior models are coded in C++ and compiled as DLL (dynamic link library) files, which can interact with the VISSIM software every time step. In this way, the acceleration of the vehicles is determined externally at every time step and then it is sent to the VISSIM for performing simulations. To capture different driver features, the scope of this modeling was focused on car-following, lane-centering and lane-changing.

We use a microsimulation framework in order to analyze micro level factors, which differ across the different levels of SAE classes. In the impact assessment, we look at the velocity profiles, lane deviations, lane changing behavior and volume throughput as measures to evaluate the performance of various SAE levels. For the safety aspect, we used the surrogate safety measure called Time to Collision (TTC) (Gettman & Head, 2003). This measure is modified to account for higher safety levels for higher SAE classes. We analyze the improvements in incidents of collisions for various levels of SAE.

CV modeling for platoons follows a similar framework to evaluate the impacts of ad-hoc platoon formation in multiple penetration scenarios of CVs. EDM is used to modify the car following behavior of CVs which are equipped with cooperative adaptive cruise control (CACC) functionality. We look at the evolution of platoons in the network and evaluate their impacts on mobility.

Next, we review signal control policies in a connected vehicle environment and identify benefits they provide over traditional-detector based control. To facilitate their implementation in the micro-simulation software VISSIM, we also propose a framework using intersection-based network model in VISSIM COM Interface to simulate infrastructure-based communication in the network.

5.4 Contents

Part 2 of the report is structured in the following way: (5) Outline (6) Autonomous Vehicles: Modeling and Impact Assessment (7) Platooning with Connected Vehicles (8) Signal Control with Connected Vehicles (9) Conclusions.

6. AUTONOMOUS VEHICLES: MODELING AND IMPACT ASSESSMENT

6.1 Framework

We analyze AVs in the SAE contexts to bring out the improvements and features for various levels of automation. In this framework, we map the various automated driver features with each SAE levels. The various automated driver features are defines as below:

1. Car-following behavior
2. Lane-centering behavior
3. Lane-changing behavior

Below we discuss the various SAE level in the context of control and Operational Design Domain (ODD).

6.1.1 Description of SAE Levels

The Society of Automated Engineers (SAE) came up with a definition of various levels of autonomy. These defined levels of SAE were adopted by NHTSA in 2016. See Figure 4.2 for details on the SAE levels.

As we can see from Figure 4.2, SAE 0 pertains to human driving behavior where human controls all driving functions. The responsibility of longitudinal, lateral, lane changing and other decisions are on the human driver. SAE Level 1 is the first level of automation that is introduced in driving. In this level, either the steering or the breaking and acceleration control is taken care by the system. For SAE Level 2, both the functions of steering, braking and accelerating are in control of the system in certain driving modes. The human up until this level does the monitoring of the environment. This changes as we go to higher SAE levels, the system monitors the environment and makes the decision who controls the vehicle based on driving environment. In the driving mode that comes under the Operational Design Domain (ODD) of the vehicle the control of certain/all functions are maintained by the system. Operational Design Domain is the sphere where a set of predetermined conditions for system control are satisfied.

For SAE Level 3, the vehicle is under complete autonomous control under certain condition. For example, Audi's traffic jam assist functionality is completely autonomous under 30 mph (Audi Technology Portal, 2015). This relieves the driver from the responsibility of the constant need for monitoring while in traffic congestion. In SAE 3, the cases where the vehicle is outside the ODD the control has given back to the human.

SAE 4 is completely autonomous under ODD. If the vehicle goes outside the ODD, for example if there is a bad weather condition or the lane markings are not clear, the vehicle assumes minimal risk conditions either by bringing the vehicle safely to a stop or by reducing the speed to satisfy the minimal risk condition. In SAE 5, the vehicle is completely autonomous under all conditions of road, environment etc.

6.1.2 SAE Modeling

In this section, we discuss the mathematical modeling for the driver features and define the parameters used for human and system control.

6.1.2.1 Car-Following Models

6.1.2.1.1 Human Control**.** The intelligent driver model (IDM) is used to model human car-following behavior. In spite of the fact that IDM is a simple car following model, it has been shown to quantitatively that it models human driving behavior well (Kesting & Treiber, 2008). It is also used as the base algorithm for ACC implementation by Volkswagen. However, the model is deterministic and in order to overcome this limitation, we introduce external stochasticity. Firstly, we will introduce the IDM model and then build upon it the stochastic extensions.

Acceleration function is assumed continuous and is affected by a number of factors that come into play. The factors include the space headway between the vehicle and its leading vehicle, the desired velocity, the current velocity, and the velocity difference of the vehicle from the leading vehicle. The SAE 0-acceleration function is defined by:

$$a_{SAE_0}(a_{IDM}, \varepsilon_0) = a_{IDM} + \varepsilon_0 \qquad \text{(Eq. 6.1)}$$

where, a_{SAE_0} is SAE 0-acceleration and a_{IDM} is IDM acceleration. ε_0 is an error term added to the deterministic IDM acceleration to model a stochastic SAE 0-acceleration. ε_0 follows a normal distribution with mean as $\mu = 0$ and variance as σ^2 which is non-zero and is uncorrelated with a_{IDM}. The IDM acceleration is given by:

$$a_{IDM}(s,v,\Delta v) = a\left(1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2\right) \qquad \text{(Eq. 6.2)}$$

Where, s the headway between the leading vehicle and the follower, v is the current velocity of the vehicle, δ is the free acceleration component, Δv is the velocity differential between the leader and the follower, v_0 is the desired speed of the vehicle, s^* is the desired space headway. The function for s^* is given by:

$$s^*(v,\Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \qquad \text{(Eq. 6.3)}$$

where, a is the minimum headway space, T is the desired time headway, b is the maximum desired deceleration.

Even though IDM captures human driving behavior, it is a model that is completely deterministic. The nature of traffic is anything but deterministic and hence in order to simulate real world traffic we introduce stochasticity to better reflect practical traffic flow conditions at micro level. In order to account for heterogeneity in the values of a, b, and T, we have modeled them using log-normal distribution.

We assume that the parameters are a, b, and T for vehicles follow a log-normal distribution. Hence these parameters are drawn from the below distributions.

$$\log a \sim N(\mu_a, \sigma_a^2) \qquad \text{(Eq. 6.4)}$$

$$\log b \sim N(\mu_b, \sigma_b^2) \qquad \text{(Eq. 6.5)}$$

$$\log T \sim N(\mu_T, \sigma_T^2) \qquad \text{(Eq. 6.6)}$$

The IDM parameters used in the paper are as presented in Table 6.1 The mean values of a, b, T, δ and s_0 are taken from (Kesting, Treiber, & Helbing, 2010), which were found to be the most suitable to represent human driving behavior in (Kesting & Treiber, 2008). Coefficients of variation of a, b, and T are assumed to be 20%.

The response rate and the situational awareness of SAE vehicles is assumed to increase for higher SAE levels. This is reflected in our model in the form of

TABLE 6.1
Parameters for Stochastic IDM Model

Parameter	Value settings
Highway Desired speed range (v_0)	55-88 mph
On ramp speed range	25-55 mph
Free acceleration exponent (δ)	4
Desired time gap (T)	~Log-Normal(0.33,0.2) s
Jam distance (s_0)	6.56 ft
Maximum acceleration (a)	~Log-Normal(0.31,0.2)ft/s^2
Maximum acceleration (b)	~Log-Normal(0.67,0.2)ft/s^2
Error term (ε_0)	~Normal(0.0,0.3) ft/s^2

TABLE 6.2
Mean Value of Time Headway

SAE 0	SAE 1	SAE 2	SAE 3	SAE 4	SAE 5
1.5	1.2	1.05	0.75	0.3	0.15

reduction of time headway term T in the IDM model. The mean value of the time headway used in the formulation of IDM for the various SAE levels are assumed to take the values shown in Table 6.2.

6.1.2.2 Autonomous Control. Enhanced IDM model has been shown to simulate the adaptive cruise control (ACC) feature (Kesting, Treiber, & Helbing, 2010). Hence, under autonomous control for Level 1 we used enhanced IDM. Enhanced IDM combines IDM and constant acceleration heuristic. IDM performs well under continuous headways, which is acceptable in a single line environment. However, in multiline environment where lane changes occur and hence result in discontinuous headways, IDM is very conservative. Constant acceleration heuristic improves upon this limitation assuming that vehicle do not randomly break to a stop. The formulation of Enhanced IDM is as below.

$$a_{CAH}(s,c,v_l,a_l)=\begin{cases}\dfrac{v^2a_l}{v_l^2-2s\overline{a_l}}, & if\ v_l(v-v_l)\leq 2s\bar{a}_l\\ \overline{a_l}-\dfrac{(v-v_l)^2\theta(v-v_l)}{2s}, & otherwise\end{cases} \quad \text{(Eq. 6.7)}$$

$$a_{ACC}=\begin{cases}a_{IDM}, & if\quad a_{IDM}\geq a_{CAH}\\ (1-c)a_{IDM}+c\left[a_{CAH}+b\tanh\left(\frac{a_{IDM}-a_{CAH}}{b}\right)\right], & otherwise\end{cases} \quad \text{(Eq. 6.8)}$$

Where, a_{CAH} is the constant-acceleration heuristic (CAH) acceleration, v_1 is the velocity of the leading vehicle, a_1 is the acceleration of the leading vehicle, $\overline{a_l}$ is the effective acceleration $= \min(a_1, a), \theta$ is the Heaviside-step function and c is the coolness factor which ranges from zero to one. The Heaviside-step function has a value 1 when v–v_l is positive in value, and zero otherwise. This ensures that a reduced acceleration is only observed when the leader vehicle is moving slower than the follower. The coolness factor c is which determines how sensitive the driver is to changes in the gap with the leader. $c=0$ corresponds to IDM itself, which defines a conservative driving behavior. On the other hand, $c=1$ means that the behavior is too relaxed. With this framework, it has been shown that a_{ACC} is always higher than a_{IDM} and the acceleration profile of cars modeled after the Enhanced IDM have a more relaxed response to discontinuous headways which results in improved mobility. Detailed discussion on the implication of the model's formulation can be found in (Kesting, Treiber, & Helbing, 2010).

Enhanced IDM (EIDM) is again a deterministic model. We extend this model by making stochastic terms to the model. Below is the formulation for the stochastic version of EIDM.

$$a_{SAE_1}(a_{ACC},\varepsilon_1)=a_{ACC}+\varepsilon_1 \quad \text{(Eq. 6.9)}$$

$$\sigma^2_{SAE_1}=\frac{\sigma^2_{SAE_0}}{k} \quad \text{(Eq. 6.10)}$$

where, ε_1 follows a normal distribution with mean as $\mu = 0$ and variance as $\sigma^2_{SAE_1}$ which is non-zero and is uncorrelated with a_{IDM}. Here we assume $\sigma^2_{SAE_1}$ that is lower than $\sigma^2_{SAE_0}$ by a factor of k where k is >1. In our model k = 10.

6.1.2.3 Lane Centering

6.1.2.3.1 Human Control. Human control: In SAE Level 2 we look at automating the lateral position of vehicles. The lateral positions of vehicles is modeled as an autoregressive time series model developed by Dawson, Cavanaugh, Zamba, & Rizzo (2010). In the time series model, Y_t is the lane position of the car at time t. $Y_t = 0$ when the vehicle is in the center of the driving lane, $Y_t<0$ corresponds to when the vehicle is left of the center lane, and $Y_t>0$ corresponds to when the vehicle is on the right of the center lane. In a first order time series, the vehicle's lateral position depends on the weighted average of the previous three time steps plus a signed error term. Therefore, the formulation for the lateral position for time step t is as below

$$Y_t=\beta_1 Y_{t-1}+\beta_2 Y_{t-2}+\beta_3 Y_{t-3}+|e_t|I_t \quad \text{(Eq. 6.11)}$$

$$\log\left(\frac{p_t}{1-p_t}\right)=\gamma_0+\gamma_1 Y_{t-1} \quad \text{(Eq. 6.12)}$$

Where, Y_{t-1}, Y_{t-2} and Y_{t-3} are the lateral positions of the vehicle at time t–1, t–2 and t–3 respectively, e_t is the error term, which follows a normal distribution, and I_t is 1 or -1 depending upon the value of p_t which is assumed to have a functional form following the logistic model given in above. Dawson et al. (2010) calibrated this model, which is used in our study. Δy is the difference between the current lateral position and the future lateral position.

The lateral position has given as an input to VISSIM as an angle instead of the position itself as the API is designed is such a manner. Below is the transformation of the future lateral position to an angle (in radians).

$$\theta_{SAE} = d_{SAE}\theta \quad \text{(Eq. 6.13)}$$

$$\frac{\Delta y}{\Delta x} = \theta \quad \text{(Eq. 6.14)}$$

$$\Delta x = vt \quad \text{(Eq. 6.15)}$$

where, Δy is the difference between the future lateral position and the current lateral position, Δx is the difference between the future longitudinal position and the current longitudinal position and t is the time-step of analysis, which is 0.1 seconds. The angle θ therefore, can be approximated as the ratio of Δy with respect to Δx. d_{SAE} is the deviation factor for a particular SAE level ranging from 0 to 1. The lower the value of the deviation factor, the lower the tendency for deviation of the car from the centerline of the lane. Under human control d is assumed to be one.

6.1.2.3.2 Autonomous control. The lane centering for autonomous vehicles has a lower deviation tendency compared to lateral deviation while under human control as the lane centering accuracy of automated system will be higher than that of humans. The deviation factors for autonomous lane centering is assumed to be 0.5.

6.1.2.4 Lane-Changing Models

6.1.2.4.1 Human Control. The lane-changing model used in our framework is called MOBIL (Kesting, Treiber, & Helbing, 2007). This model was developed by the same authors who developed Enhanced IDM for ACC; hence, we also adopted their lane-changing model to maintain consistency. MOBIL is a rule-based lane-changing model, which is added as an autonomous feature to Level 3 vehicles. It takes into account two important factors while making a lane-change. The first factor is the safety factor; the algorithm makes sure that when a vehicle changes its lane, the vehicle behind it does not need to break beyond a safe breaking value. The second factor, which is used as criteria for whether a vehicle is allowed to change a lane, is based on the below conditions:

$$a_c^{'} - a_c + p\left(a_n^{'} + a_o^{'} - a_o\right) \geq \Delta a_{thr} \quad \text{(Eq. 6.16)}$$

$$a_n \geq -b_{safe} \quad \text{(Eq. 6.17)}$$

Where, c is the vehicle considering to change lane, n is upstream vehicle on the target lane, o is the upstream vehicle on the present lane, a_c is the acceleration of vehicle c on the current lane, $a_c^{'}$ is the acceleration of vehicle c on the target lane, a_o is the acceleration of vehicle o before lane change by vehicle c, $a_o^{'}$ is the acceleration of vehicle o after lane change by vehicle c. a_n is the acceleration of vehicle n before lane change by vehicle c and $a_n^{'}$ is the acceleration of vehicle n after lane change by vehicle c, p is the politeness factor. Δa_{thr} is the acceleration threshold that must be crossed in order to make a lane change. This threshold exists to make sure that a lane changing operation by a vehicle is made only when the overall weighted acceleration of the group of vehicles is above a certain level. This helps in a lower adverse impact on the neighborhood vehicles' movement. For humans we have assumed the Δa_{thr} to be $3ft/s^2$.

p is the politeness factor, which accounts for the driver's level of altruism. The politeness factor of one represents a driver who equally account for impacts on accelerations of his neighbors as much as he does for his own. This would be a highly altruistic driver. On the other hand, a politeness factor of zero would represent a driver who does not factor in the acceleration impact of lane changes to the neighboring vehicle. We have used a politeness factor of 0.5, which is a more realistic value for the parameter.

6.1.2.4.2 Autonomous Control. We assume that for autonomous lane changing the acceleration threshold will be lower as compared to human acceleration thresholds. This assumption is used in the modeling because autonomous vehicle would be able to perceive smaller acceleration threshold opportunities as compared to humans.

6.1.3 Mapping of SAE Levels with Driver Features

This section involves mapping of the various SAE levels to the different driver features, which include car-following, lane centering, and lane changing behaviors. The analysis of these models has been done in VISSIM which is a microsimulation platform using the External Driver Model (EDM) API. Using this API, we can control the driving behavior of the vehicles in the microsimulation. Below we discuss the mapping of each of the levels with the features involved at each level.

6.1.3.1 SAE Level 0. In SAE Level 0 there is no automation that is equivalent to human driving. In order to fully model the human driving at SAE Level 0 we have to model the various driving features based on the human parameters previously discussed. For car-following we used IDM. As mentioned before it mimics human car following behavior well. For the lane centering function, we use a deviation factor 1 in order to model human lane centering behavior. The acceleration threshold used for the lane-changing algorithm is taken as one.

6.1.3.2 SAE Level 1. In SAE 1 either the steering or the braking/acceleration is controlled by the autonomous system. In our model, the longitudinal control is automated to represent SAE Level 1. ACC feature is modeled using the stochastic version of EIDM.

6.1.3.3 SAE Level 2. For Level 2 along with ACC we add the feature of lane assist. Lane- keeping assist feature helps in keeping the vehicle close to the center of the lane. This feature is modeled using a third-order autoregressive time series model.

6.1.3.4 SAE Level 3. SAE Level 3 is considered to be a first level when the vehicle can go into a completely autonomous mode under certain conditions. The responsibility of monitoring the environment is transferred to the system. In our study, the vehicle is assumed to be under autonomous control when on freeways. If the vehicle is not on freeway then the control stays with the human. One of the key features unique to the SAE 3 level is the fact that when the vehicle gives control to the human, there is a transition time after which the control is handed over. These transition times, called engagement and disengagement, have been tested by a few studies (Dixit, Chand, & Nair, 2016; Merat, Jamson, Lai, Daly, & Carsten, 2014). Engagement is the action of human taking control of the driving from the system and disengagement is the action of the human ceasing to maintain control over the driving and handing it over to the system. We have used data from these studies to model the reaction time of the drivers during the transition of the control.

6.1.3.5 SAE Level 4. In SAE 4, the vehicle is completely autonomous inside its operational design domain (ODD). ODD is defined as an acceptable domain in which all the pre-specified conditions are satisfied for autonomous functioning. When the vehicle is out of ODD, it needs to assume a minimal risk condition. An example of minimal risk condition is the vehicle coming to a complete halt or reducing the speed much lower than the speed limit of the roadway. We define this speed as minimal risk condition desired speed (MRCDS). In our study we have assumed that ODD is any roadway with clear lane markings. Roadways with unclear lane marking is considered outside ODD. In this study, we analyzed the traffic impact inside and outside ODD.

6.1.3.6 SAE Level 5. SAE 5 corresponds to maximum level of automation. The system has complete control of the vehicle under all conditions. This includes road environment where the lane marking is unclear, non-standardized signs and among others.

6.1.4 Conflict Analysis

In the context of microsimulation to analyze the safety aspects of traffic flow, the framework of conflict analysis is often used (Yang, Ozbay, & Bartin, 2010). Conflicts are defined as intersection of pathways of any two vehicles on roads. These can be used as substitutes for accident data, which is much rarer and takes much time to collect. The measures used to identify and measure conflicts are known as Surrogate Safety Measures (Gettman & Head, 2003). Among these measures the most common ones are time to conflict (TTC), post encroachment time (PET), MAX D. Post encroachment time is the time taken by the follower vehicle to reach the same position as the leader vehicle. MAX D is another surrogate measure that provides the maximum deceleration of the follower vehicle in the conflict region. MAX Delta S is a surrogate measure that provides the maximum absolute speed difference between the follower and the leader vehicle. This measure captures the big differentials that many times happen in the case of accidents. From previous studies, it has been shown that there is strong correlation between the surrogate measures of safety and accident data. Shahdah, Saccomanno, & Persaud (2015) evaluated the safety levels of signalized intersections using microsimulation with TTC as the surrogate measure of safety. To predict crash risk, Li, Xiang, Ma, Gu, & Li (2016) used the conflict framework in a microsimulation setting.

Even though in these studies surrogate measure have been used in order to identify conflicts but they have been done only for human driver. Currently, no framework exists which can be used to perform a conflict analysis for autonomous vehicles of different SAE levels. For the purpose of this study, we identified TTC thresholds based on the improvement in accident risk for a particular SAE level. In order to conduct conflict analysis we have employed the Surrogate Safety Assessment Model (SSAM) software developed by FHWA. This software takes in as input the trajectory file created by VISSIM during a traffic simulation run. We have chosen to use this tool to evaluate the various SAE levels vehicle trajectories and analyze the different conflict measures provided by the tool.

6.1.4.1 TTC for SAE Levels. In this section, we formulate the different TTC thresholds for various SAE levels. TTC is most common measure used for conflict analysis in a microsimulation setting. The formula for TTC is as below.

$$TTC = \frac{p_i - p_j}{v_i - v_j} \qquad \text{(Eq. 6.18)}$$

Where i is the leader and j is the follower. p_i is the position of the leader and p_j is the position of the follower. v_i is the speed of the leader, v_j is the speed of the follower.

A lower value of TTC usually signifies a higher conflict probability but this is in a context where all the vehicle types are the same. In our study, we account for six different types of SAE level vehicles. Therefore, the assumption that a lower TTC represents a higher level of accident risk is not completely accurate. In order to identify the risk level of autonomous vehicles there is a need for identifying the thresholds applicable to each SAE level.

In previous studies, many researchers have attempted to define the threshold TTC which has ranged from one to 6 (Huang, Liu, Yu, & Wang, 2013; Habtemichael & Santos, 2015; Al-Ghandour, Schroeder, Williams, & Rasdorf, 2011). In our study, we will assume the TTC threshold for SAE 0 as 6 secs.

Using the TTC threshold for SAE 0 as the base value, we use an improvement factor based approach to arrive at TTC thresholds for SAE Levels 1 to 5. These improvement factors are derived from the manner of accidents from 10 counties in Indiana using 2013, 2014, 2015, 2016 and 2017 accident data, which includes detailed information about the cause of each recorded accident. We first map these manners of collision to specific autonomous features. The improvement factor I_j for every SAE level j is then defined as the percent reduction in accidents (to the nearest 5) due to the autonomous features that first appear in that level. This is based on the assumption that once a feature is automated, accidents corresponding to it would be eliminated. Then, we use the formulation below to arrive at TTC thresholds for different SAE levels. Improvement factors and TTC thresholds obtained henceforth for different SAE levels are listed in Table 6.3 and Table 6.4 respectively.

$$TTC_{threshold_{SAE\,level_i}} = TTC_{threshold_{SAE\,level_0}}\left(1 - \sum_{j=0}^{i} I_j\right) \tag{Eq. 6.19}$$

6.1.4.2 Trajectory Analysis for Various SAE Levels. The trajectory file, which is output by VISSIM after a simulation run, is analyzed using SSAM. Even though SSAM is a very useful tool that can analyze trajectory from most popular commercial software, it has few limitations. One of the limitation is that it cannot distinguish the separation in grade between two roads. This can result in false conflicts. These false conflicts need to be filtered out in order to identify the real conflict in the network. The SSAM software can provide the following measures for each conflict. TTC, PET, MAX D, deceleration rate (DR), MAX Delta S etc. Once the trajectory is analyzed and the conflicts are identified and filtered, they need to be compared against the SAE levels thresholds previously identified. This will give us a more accurate picture of the conflicts instead of standard routine conflict analysis.

TABLE 6.3
Improvement Factors for SAE Level

SAE Level	Improvement factor
0	0.0
1	0.35
2	0.15
3	0.15
4	0.2
5	0.05

TABLE 6.4
TTC Thresholds

SAE 0	SAE 1	SAE 2	SAE 3	SAE 4	SAE 5
6	3.9	3.0	2.1	0.9	0.6

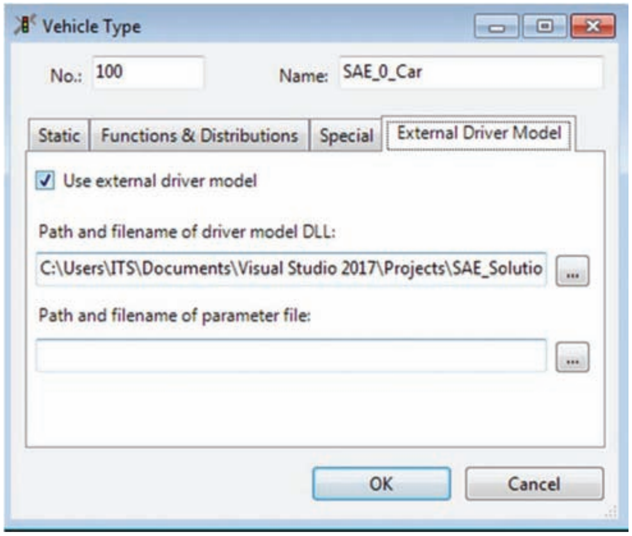
6.1.5 Micro-Simulator Settings

The VISSIM micro-simulator is used to model the various SAE levels and also to analyze and evaluate their impacts. The default model in VISSIM are replaced by the car-following, lane changing and lane – centering functions as defined previously in our model. EDM is the channel via which these models are communicated to VISSIM (see Figure 6.1).

6.1.5.1 Vehicles Type—SAE Levels. Next, we define the various SAE levels in VISSIM (Figure 6.2). For each SAE level a vehicle type has been defined which is linked to DLL specifically modeled to mimic that SAE level.

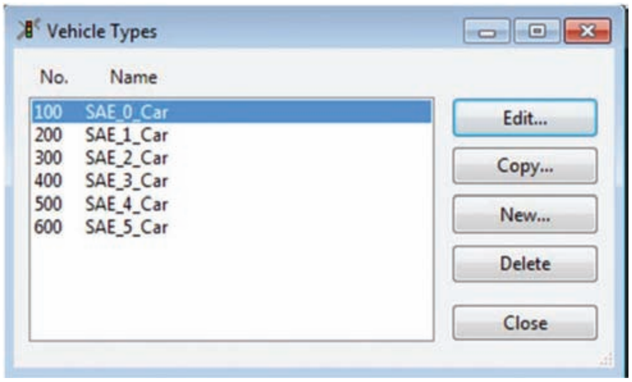
6.1.5.2 Vehicle Class—SAE Levels. Each of the vehicle types that were defined in the previous subsection are classified under different vehicle classes ranging from SAE 0 class to SAE 5 class. As can be seen in Figure 6.3 we can see the different vehicle classes for each SAE levels.

6.1.5.3 Volume Composition—SAE Levels. We define six different volume compositions to represent each SAE levels. Each of the volume compositions are



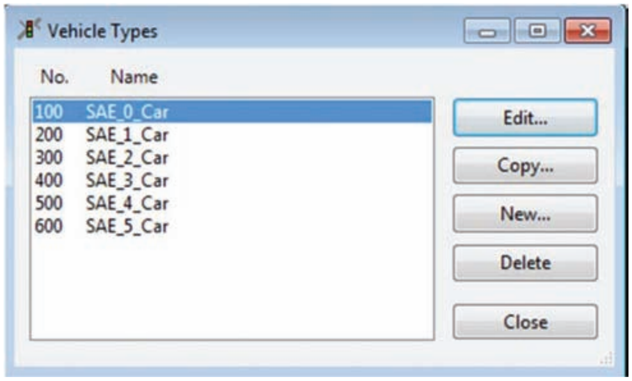
No.: 100
Name: SAE_0_Car
☑ Use external driver model
Path and filename of driver model DLL:
C:\Users\ITS\Documents\Visual Studio 2017\Projects\SAE_Solutio
Path and filename of parameter file:

Figure 6.1 External Driver Model linked to VISSIM.



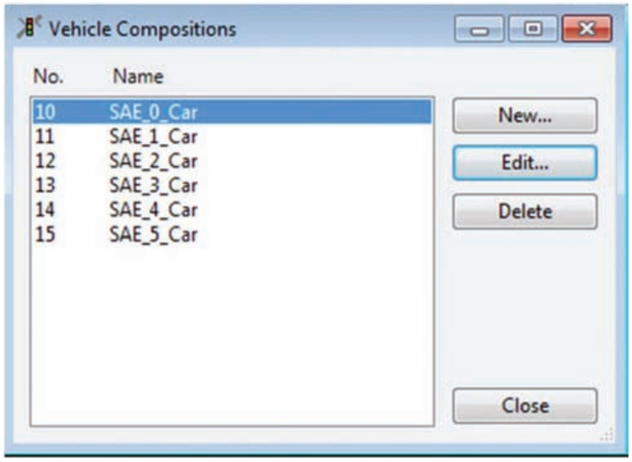
No.	Name
100	SAE_0_Car
200	SAE_1_Car
300	SAE_2_Car
400	SAE_3_Car
500	SAE_4_Car
600	SAE_5_Car

Figure 6.2 Vehicle types for different SAE levels.



No.	Name
100	SAE_0_Car
200	SAE_1_Car
300	SAE_2_Car
400	SAE_3_Car
500	SAE_4_Car
600	SAE_5_Car

Figure 6.3 Vehicle classes for different SAE levels.



No.	Name
10	SAE_0_Car
11	SAE_1_Car
12	SAE_2_Car
13	SAE_3_Car
14	SAE_4_Car
15	SAE_5_Car

Figure 6.4 Vehicle compositions for different SAE levels.

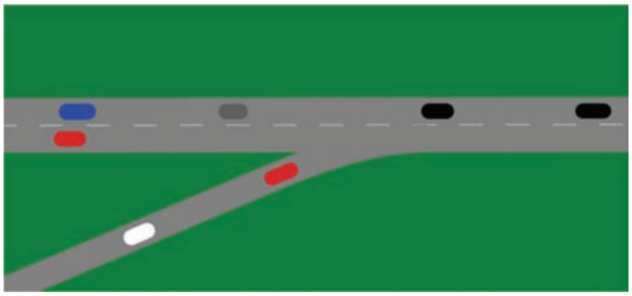


Figure 6.5 Test network.

assume to have 100% penetration. Figure 6.4 shows the different vehicle compositions for different SAE levels.

6.2 Experimental Design for Mobility Impacts

6.2.1 Network Description

For the purpose of mobility analysis we have utilize two networks. The first network is more of a test network that is able to provide a very clear visual understanding of the micro-dynamics of the SAE models created. The second network we have used is I-70 and I-465 interchange (Figure 6.6). This is a network, which in many ways is a complex combination of the network tested in the first place. For this network, we have estimated the overall micro-level volume improvements due to different SAE levels.

6.2.1.1 Network 1. The test network designed for the simulations, as illustrated in Figure 6.5, is a 1-mile straight two-lane highway with a single-lane on-ramp joining the highway at 0.3 mile. Traffic from on-ramps into the highway are typical scenarios for traffic congestion and bottlenecks, and hence this particular network was chosen to analyze the performance of different SAE levels in such a network. The traffic is composed of passenger cars. The cars are modeled to be 12 ft long and 4.5 ft wide, which is the standard size provided in VISSIM. First, we choose a homogeneous traffic to be able to analyze the effects of the various SAE levels on the traffic. In addition, the simulations for each SAE level vehicles was run separately assuming 100% penetration of the particular SAE level vehicle. The traffic flow on the highway is assumed to be 800 veh/hr/lane and the traffic flow on the on-ramp is 300 veh/hr/lane. The speed distribution of the vehicles is 50mph to 80mph. For each SAE level there was a vehicle type created in VISSIM as shown in Figure 6.2. The created vehicle types were linked to EDM DLLs as a shown in Figure 6.1. In the second part of the analysis, we analyzed the various impacts on traffic for different penetration of SAE levels.

6.2.1.2 Network 2. Network 2 is the interchange between I-70 and I-465, which is located at the east junction of the two routes. In this network, there are eight merging points and seven diverging points. The traffic volume on the freeway is assumed to be 1,000 vehicles per lane per hour. In total, the entire network has 20,700 vehicles per hour.

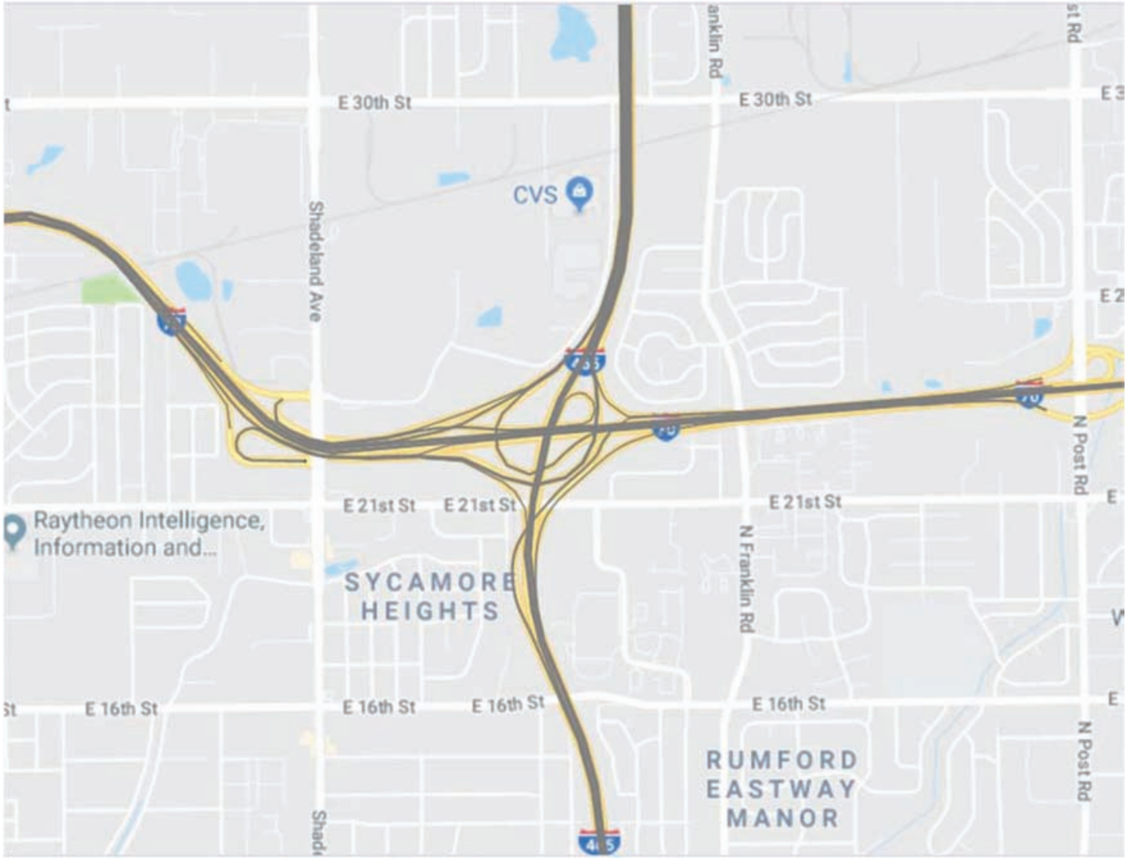


Figure 6.6 I-70/I-465 freeway interchange.

6.2.2 Mobility Impact Analysis

Given these networks, we have identified two unique type of traffic flows that can be analyzed given the network: 1) vehicles originating on the highway and continue traveling on it, and 2) vehicles entering the highway through the on-ramp. In this study, we present the impacts on these flows for each of the SAE levels. Below we discuss the impacts of various SAE levels and then analyze the impacts for different penetration levels. It may be noted that SAE level impacts (section 6.2.2.1) and penetration impacts (section 6.2.2.2) were obtained from simulation runs on network 1. We also analyze volume impacts at specific data collection points in the simulation (section 6.2.2.3). For these volume impacts, we use network 2.

6.2.2.1 SAE Level Impact. Here we discuss the various mobility related impact of the different SAE levels.

6.2.2.1.1 SAE 0 and SAE 1. In this section, we look at the mobility impacts of SAE 0 and SAE 1 vehicles. SAE 0 vehicles are modeled using IDM, which are more conservative, compared to EIDM. From Figure 6.7 we can see that SAE 0 vehicles in the graph have their minimum velocity go down to 46 mph. On contrary, SAE 1 vehicles have a less conservative reaction to the merging vehicles and hence their speeds do not fall as much. For a coolness factor of 0.5 the speed of the vehicle fall down only until 48 mph. When the coolness factor is one, the minimum speed bottoms out at 50.5 mph.

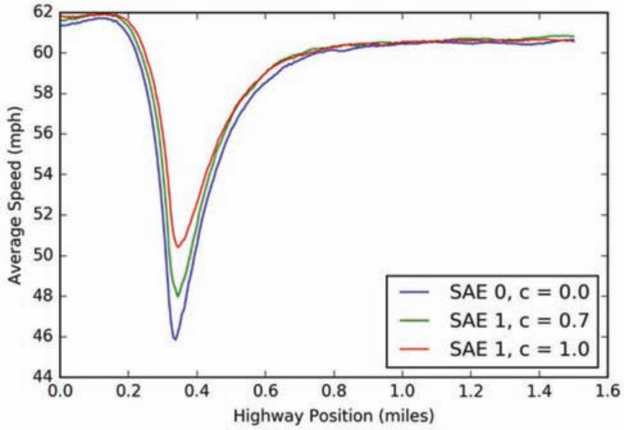


Figure 6.7 Speed profiles of SAE 0 and SAE 1 vehicles (with different coolness factors).

6.2.2.1.2 SAE 2. In this section, we look at the results from the lane-keep assist autonomous functionality.

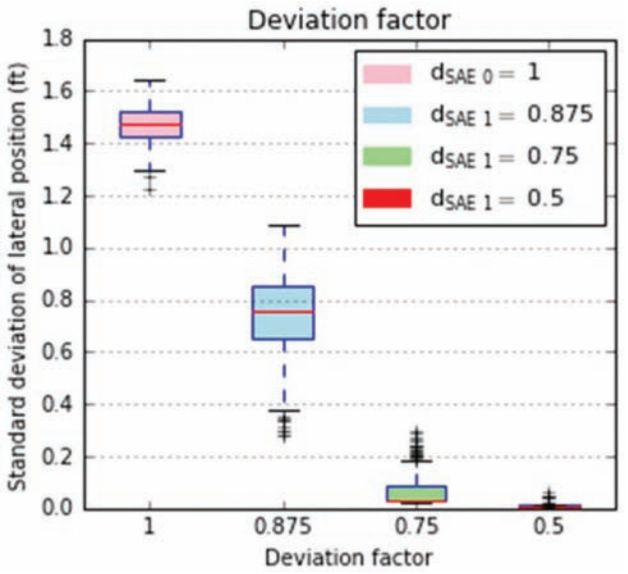


Figure 6.8 Box plots representing the standard deviation of lateral positions with different deviation factors for SAE 1 and SAE 2.

We then compare it to the human lane-centering behavior. We can see that in Figure 6.8 as the deviation factor decreases from 1 to 0.5 the mean of standard deviation of the SAE Level 2 vehicles go down. The box plot itself shifts lower as the standard deviation quartile range itself moves lower. These results show that the as the deviation factor decrease the movement of the vehicles around the centerline decreases as well. The human driver deviation as shown in the left most box plot is higher than the SAE Level 2 deviation in terms of the mean and the quartile range.

6.2.2.1.3 SAE 3. In this section, we see how different acceleration thresholds result in different lane changing behavior and how that impacts mobility. Figure 6.9 shows the acceleration thresholds for 0.32, 1.6, 3.2, 6.4 ft/s^2. We see that number of lane changes drop significantly as the thresholds becomes equal to and greater than 1.6 ft/s^2. We observe from Figure 6.10 an increase in mobility as the acceleration thresholds decrease but at the same time, these improvements are not as significant as it was in the case of SAE 1 vs. SAE 0. Figure 6.11 shows change in lateral deviation as control is passed from human driver to the vehicle, which significantly drops from SAE level 1 to SAE level 4.

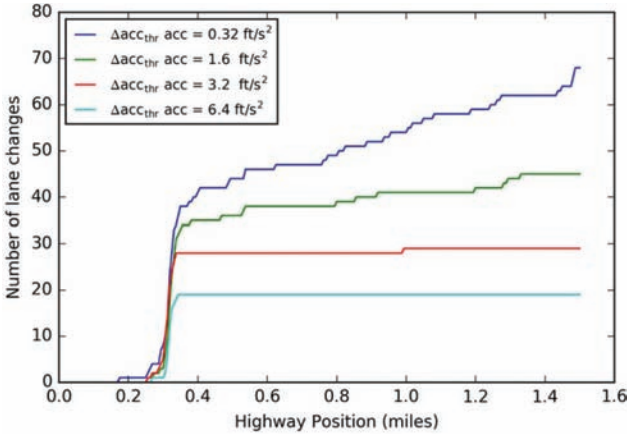


Figure 6.9 Total number of lane changes for different levels of threshold accelerations for SAE 3 vehicles.

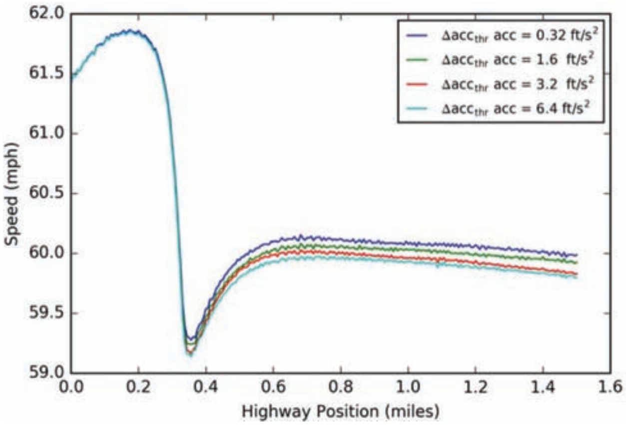


Figure 6.10 Speed profile for different levels of threshold accelerations for SAE 3 vehicles.

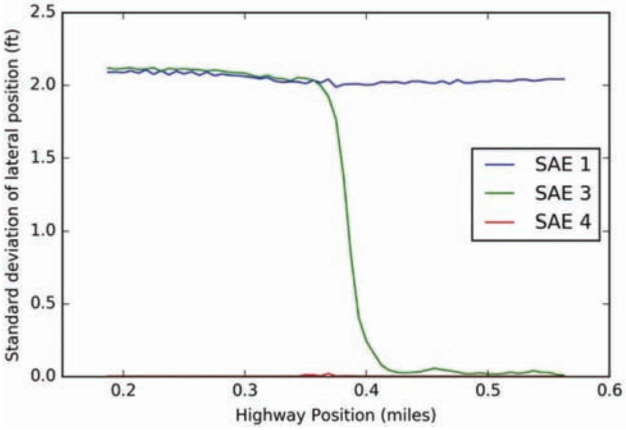


Figure 6.11 Change in lateral deviation with shift in control from human to autonomous.

6.2.2.1.4 SAE 4 and SAE 5. In Figure 6.12, we look at the performance of SAE 4 and SAE 5 vehicles on a roadway with a section having unclear lane marking. The section from 1.6 to 1.8 mile is assumed to have unclear lane marking. While SAE 4 travel through this roadway and pass through this section, they enter a region outside their ODD. In the scenario, they attempt to attain minimal risk conditions status by decelerating to MRCDS. We have chosen MRCDS as 30 mph and 45 mph. We see that these speeds decrease to these levels as SAE Level 4 vehicles pass the section and then accelerate to their desired speed.

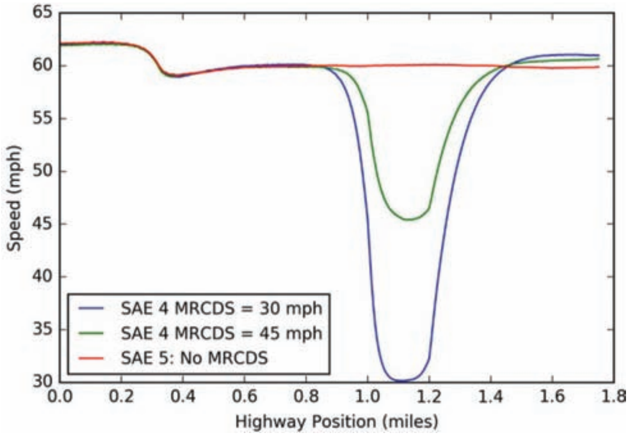


Figure 6.12 Speed profiles for different minimal risk speeds in unclear lane markings area.

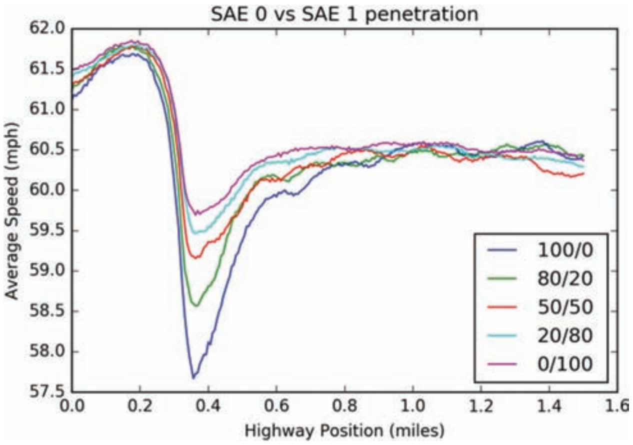


Figure 6.13 Speed profiles for different penetrations of SAE 0 and SAE 1 vehicles.

6.2.2.2 Penetration Impacts

6.2.2.2.1 SAE 0 and SAE 1. Figure 6.13 shows the mobility impacts of various penetration levels of SAE 0 and 1 vehicles. The minimum speed for 100% penetration of SAE 0 vehicles is 57.6 mph. 20% penetration of SAE 1 vehicles improves the minimum speed to 58.5 mph. From the figure, we can see that SAE 1 vehicles do no improve the speed significantly for higher penetration of these vehicles as much as it does for lower penetration.

6.2.2.2.2 SAE 1 and SAE 2. We can see from Figure 6.14 the mean and quartile range for the boxplot for 100% penetration of SAE 1 is 2.1 and between 2 to 2.2 respectively. When the penetration of SAE 2 is 20%, the quartile range is extended on the lower end. When the penetration is 50, the quartile range is the maximum that is expected because of the fact that there are two types of vehicles with different standard deviations in equal proportion. The IQR range decreases after this, since SAE 2 vehicles dominate most of the traffic. Finally, under 100% SAE 2 penetration the IQR ranges from .25 to .28. As the penetration of SAE 2 increases, we see the median falling from 2.1 to 0.26.

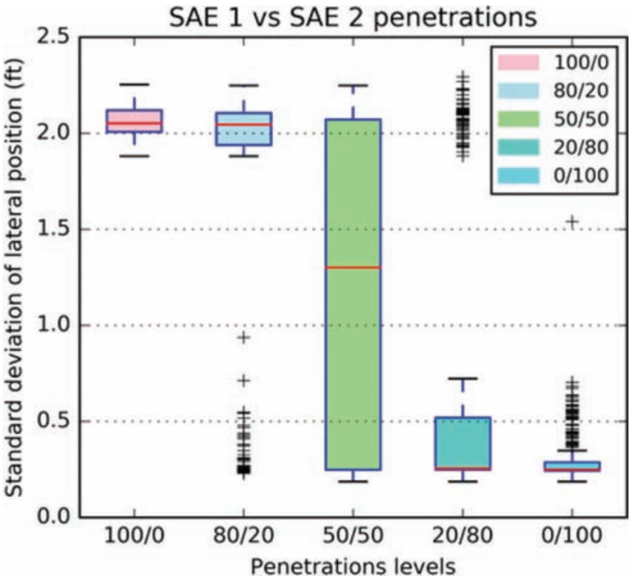


Figure 6.14 Standard deviation for different penetrations of SAE 1 and SAE 2 vehicles.

6.2.2.2.3 SAE 2 and SAE 3. In this section, we analyze the mobility improvements with increasing penetration of SAE 3 vehicles. The lane changing maneuvers of SAE 3 are superior and hence result in higher mobility. As seen before the increase in mobility is not very large and hence we look at the penetration for the case when SAE Level 3 vehicles have 50% penetration.

We see that the improvement in mobility is not in proportion to the penetration levels. This is further corroborated by Figure 6.15, which shows the cumulative number of lane changes for the three different scenarios. At 50% penetration, the number of lane changes is lower than expected (see Figure 6.16).

6.2.2.2.4 SAE 3 and SAE 4. In this section, we look at the impact on traffic characteristics for various penetration for SAE 3 and SAE 4 vehicles. From Figure 6.17, we can see that the range of standard deviation for 100% penetration of SAE 3 vehicles has an inter-quartile range (IQR) of 0.8 to 0.9 and the median value is at 0.85. When there is 20% of SAE 4 vehicles, the IQR increases from 0.75 to 0.88 and the median value decreases 0.81. When the SAE 4 penetration increases to 50% in that scenario the IQR is the highest, ranging from 0.1 to 0.8 and the median value at 0.55. The penetration increases to 80% the IQR decreases significantly ranging from 0.1 to 0.38 with

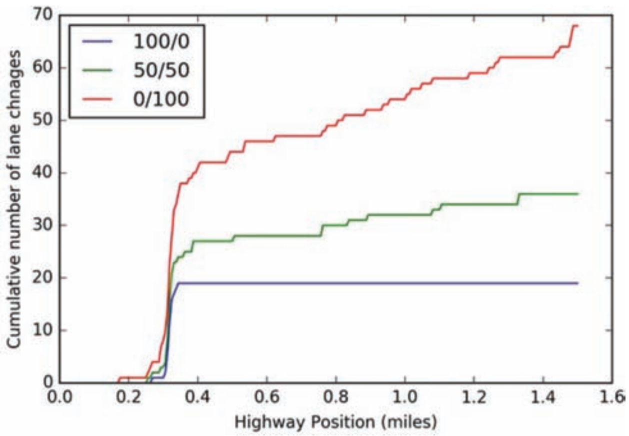


Figure 6.15 Cumulative lane changes for different penetrations of SAE 2 and SAE 3 vehicles.

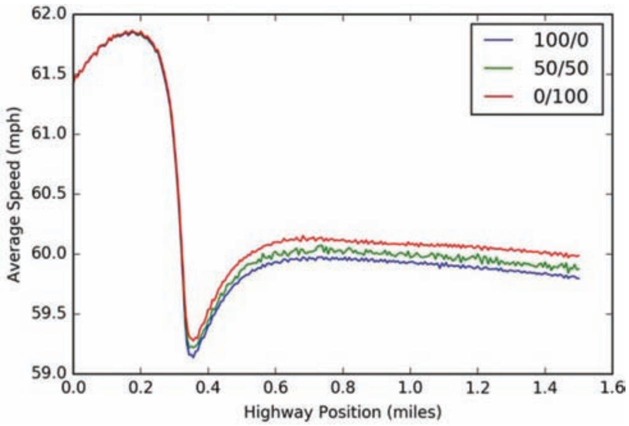


Figure 6.16 Speed profiles for different penetrations of SAE 2 and SAE 3 vehicles.

the median 0.11. At 100% penetration, we can see that the IQR expectedly is in the range 0.08 to 0.12 and the median is at 0.1.

6.2.2.2.5 SAE 4 and SAE 5. In this section, we analyze the impact of various SAE 4 and SAE 5 volume mixes on traffic mobility. As mentioned before mile 1 to mile 1.2 is a region with unclear lane markings. Therefore, for SAE 4, this region will be outside the ODD. Here we look at how the speed profiles are impacted for various penetration levels of SAE 4. In Figure 6.18, we see that for 20% penetration for SAE 4, the overall mobility impact on traffic is significantly high. The extent of this impact is especially notable when it is compared to the mobility impact due to further penetration of SAE 4 vehicles. This implies that small penetration levels of SAE 4 vehicles, when outside their ODD, can result in notable impact on traffic mobility.

6.2.2.3 Volume Impacts. In this section, we look at the volume impacts of SAE levels on the I-70/I-465 road network (network 2). We identify five data collection point that have diverging or merging traffic (see figure 6.19). The data collection points are identified such that there are conflicting traffic flows that affect the overall flow, and we evaluated the performance of the various SAE levels at these points. Figure 6.20 show these data collection points in more detail. From Figure 6.21 we can see that the SAE level automation result in improved capacity. The network was tested for the capacity flow, and we calculated the volume going past the data collection point for each SAE level. We can see that due to the reduction in headway across the various SAE levels the volume throughput can increase significantly. The volume throughput of SAE 1 is 33% more than the volume throughput of SAE 0. Similarly, the throughput of SAE 5 is about 2.5 times the throughput of SAE 0. This can result in significant increases in road capacity.

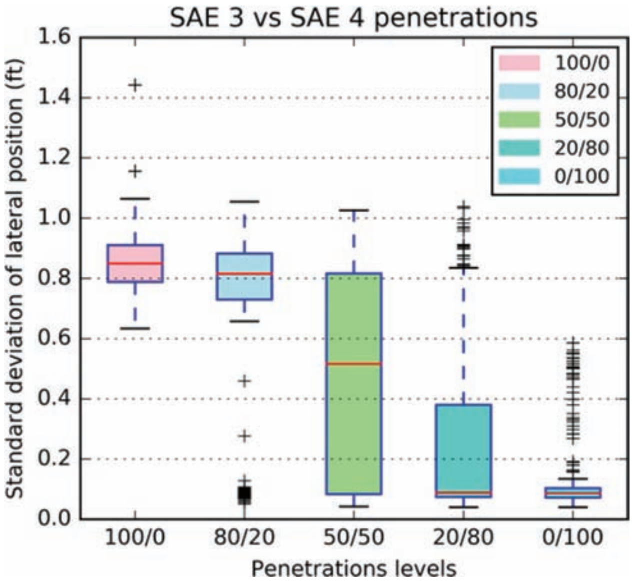


Figure 6.17 Standard deviation for different penetrations of SAE 3 and SAE 4 vehicles.

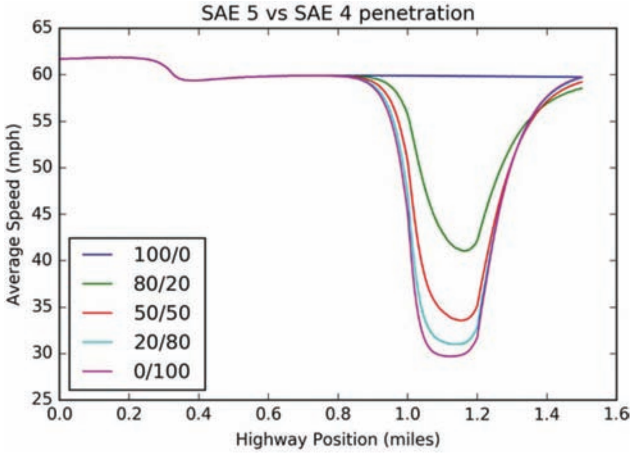


Figure 6.18 Impact on speed for different penetrations of SAE 4 and SAE 5 vehicles.

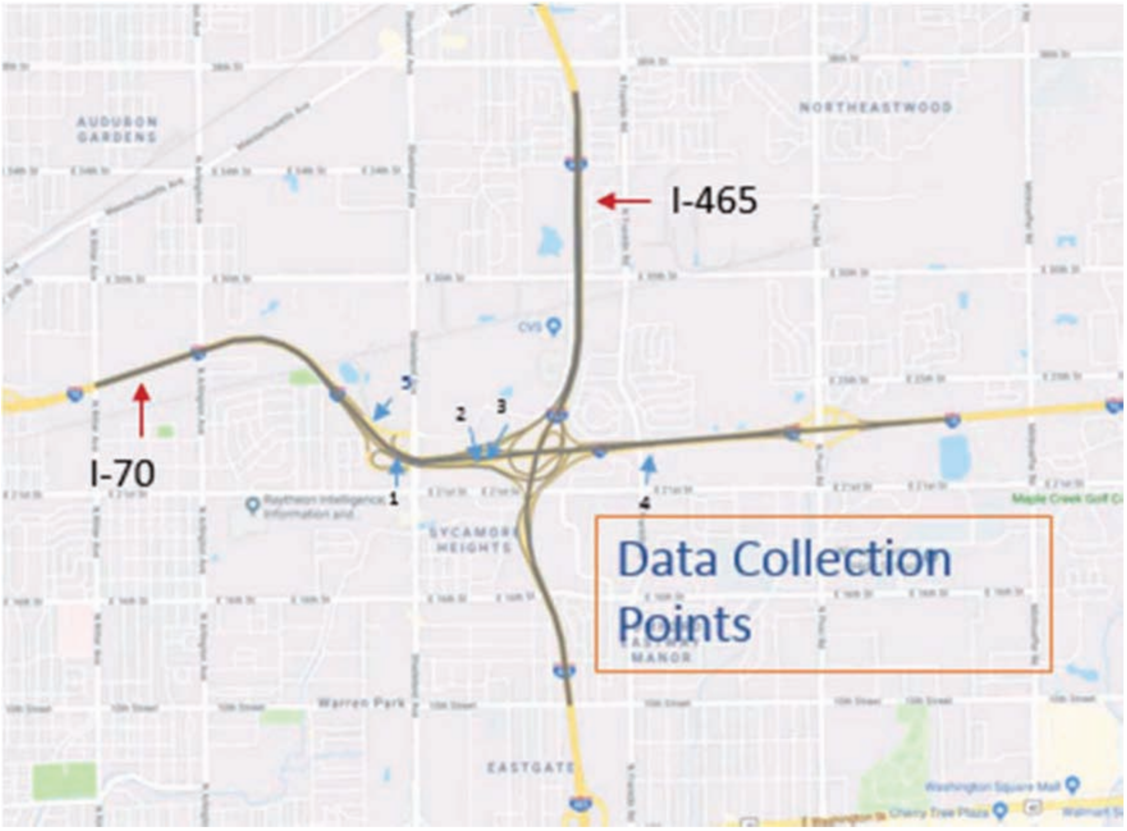


Figure 6.19 Data collection points on I-70/I-465 intersection.

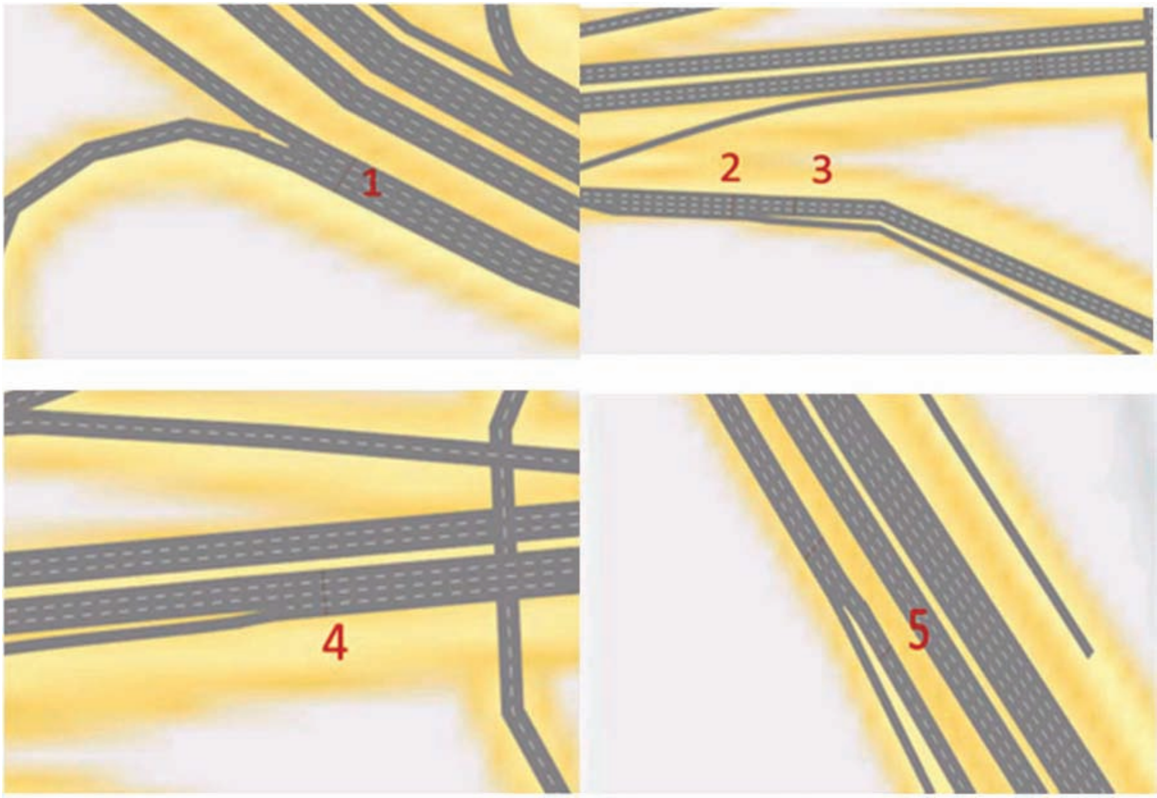


Figure 6.20 Data collection points in higher resolution.

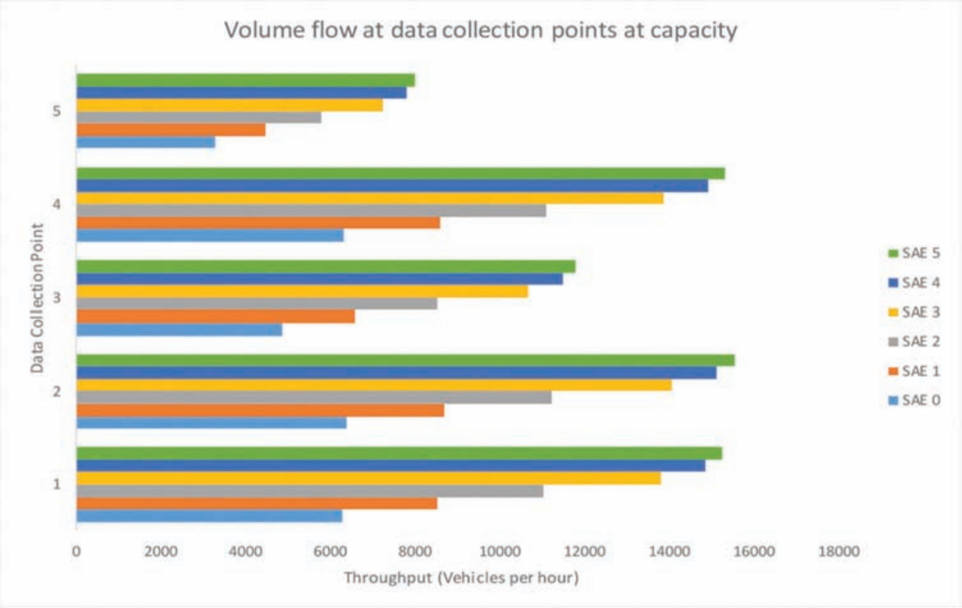


Figure 6.21 Volume throughput at capacity at the data collection points.

6.3 Experimental Design for Safety Impacts

To conduct the safety analysis, in intersection of different SAE levels we have designed a three by three grid network which has nine signalized intersections and represents a typical downtown area. We also use the conflict analysis framework described in the previous section in order to identify conflicts in a micro-simulation setting. TTC has been used as the main surrogate safety measure to analyze the conflicts. As mentioned above we have introduced different TTC thresholds for various SAE levels.

6.3.1 Network Description

Network 1 has nine signalized intersection with a distance of 0.33 miles between each signal. This represents the downtown grid observed in multiple cities. The signal phases are coordinated. The horizontal traveling traffic is presented with the green signal at the same time and consequently all the vertical traveling vehicles see green at the same time. The flow is rate is 400 veh/lane/hour and the average mean speed is 30 mph.

6.3.2 Safety Impact Analysis

The safety analysis done on the Figure 6.22 was done using six different vehicle compositions. Each of these compositions consisted of 100% penetration of various SAE levels. In the below impact analysis we will show the conflict on this grid for different SAE levels using the inputs SSAM software (see Figures 6.23, 6.24, 6.25, 6.26, 6.27, 6.28, and 6.29). The TTC thresholds for the different SAE levels are as mentioned in Table 6.4: TTC Thresholds. Each of the simulations is run and then the conflicts, which have time to collision value below the threshold value, is identified. We can see that the SAE 0 vehicles have many conflicts, which include right turn movements as well as rear-end conflicts when coming to a stop at the traffic lights. As the SAE levels increase, the number of conflicts are significantly reduced due to the reduced TTC threshold applicable to them. Right turn conflicts reduce rapidly since the higher SAE level vehicles more easily detect turning vehicles. At the same time, the rear end conflicts also reduce resulting in a significant reduction in conflicts. From SAE Level 0 to SAE Level 1 due to the reduction in threshold TTC the conflicts reduce by over 305. Moreover, from SAE 0 to SAE 5 the conflicts reduce to the tenth of the conflicts in SAE 0.

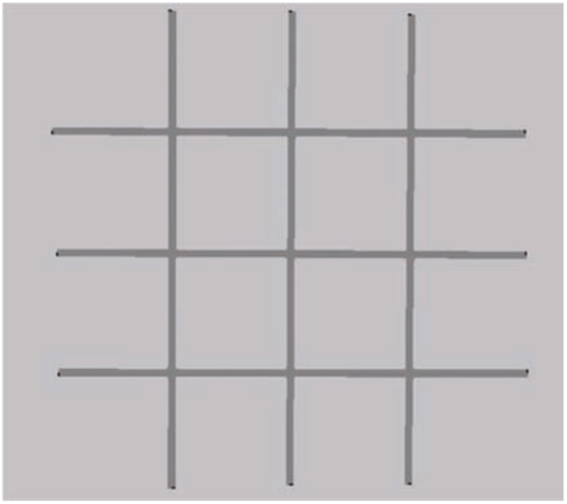


Figure 6.22 Three by three signalized grid.

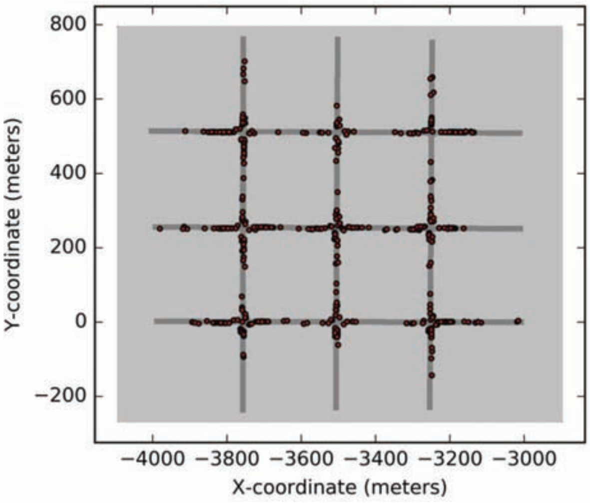


Figure 6.23 Conflicts for SAE Level 0 vehicles.

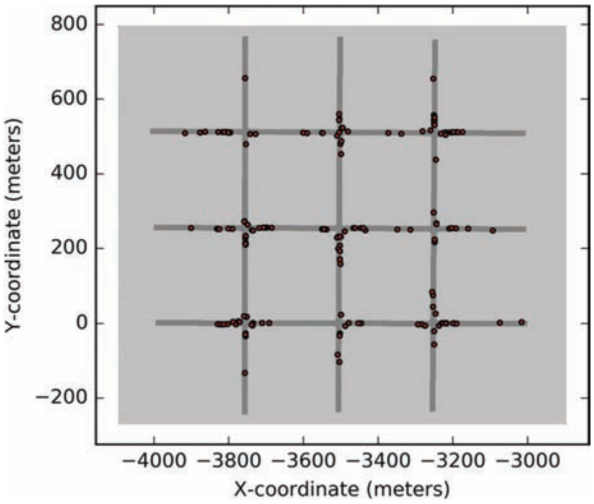


Figure 6.24 Conflicts for SAE Level 1 vehicles.

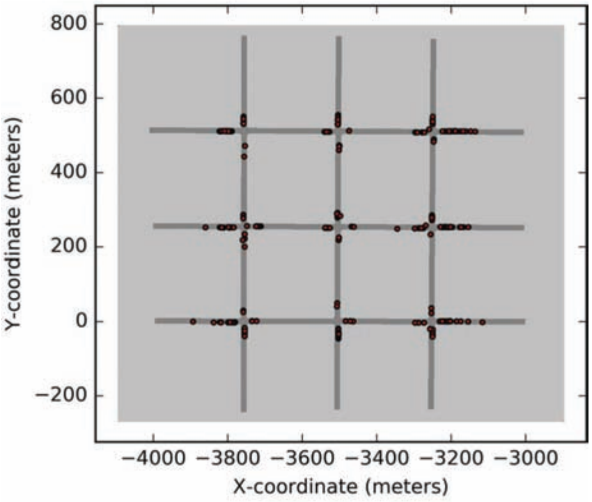


Figure 6.25 Conflicts for SAE Level 2 vehicles.

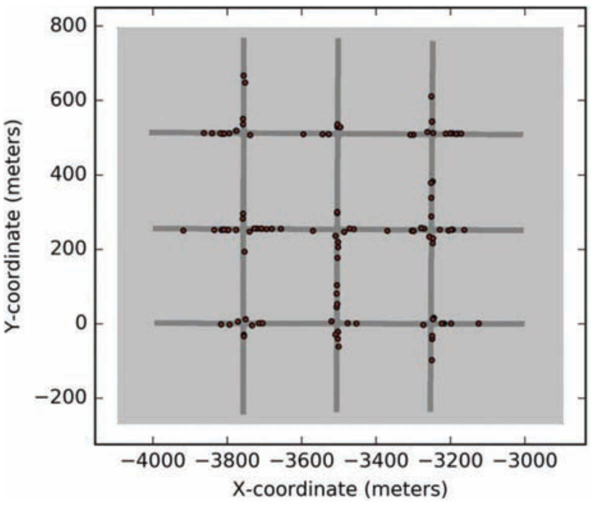


Figure 6.26 Conflicts for SAE Level 3 vehicles.

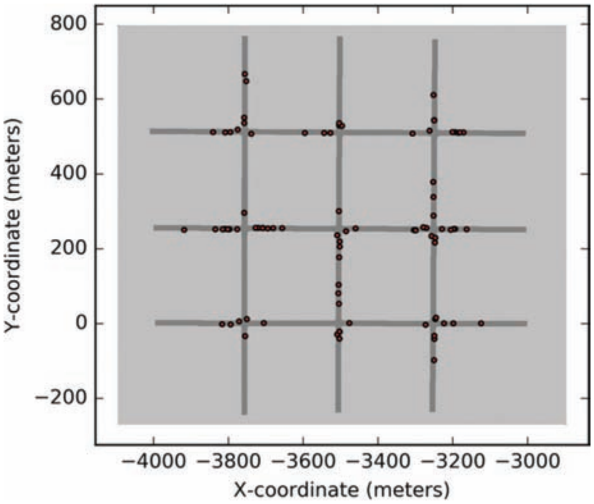


Figure 6.27 Conflicts for SAE Level 4 vehicles.

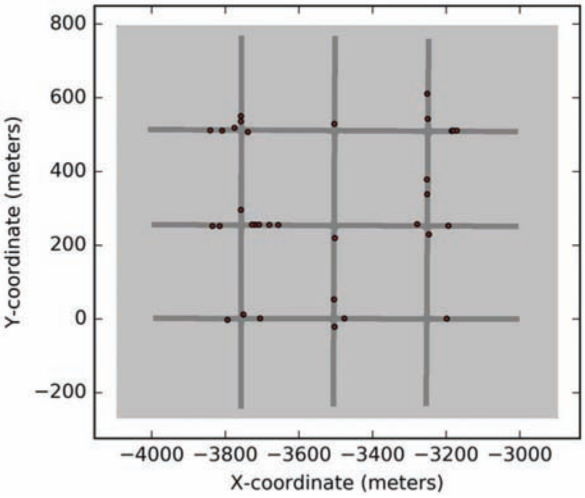


Figure 6.28 Conflicts for SAE Level 5 vehicles.

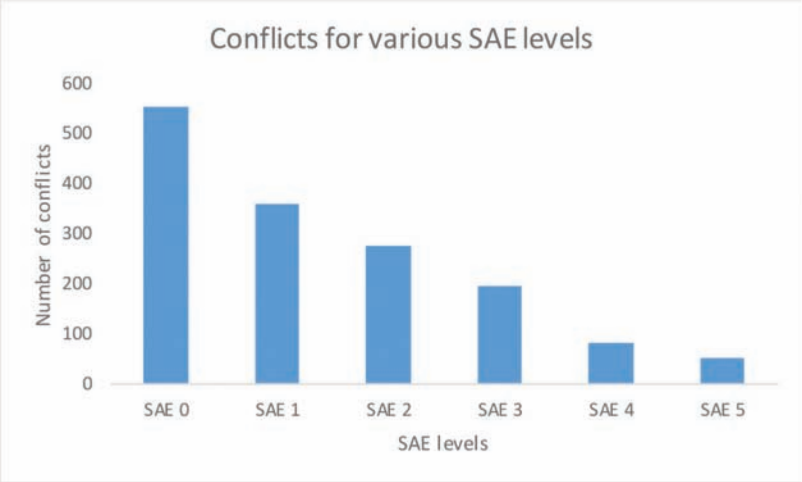


Figure 6.29 Conflicts for SAE levels.

7. PLATOONING WITH CONNECTED VEHICLES

7.1 Framework

With vehicle-to-vehicle (V2V) communication technology, equipped vehicles can share real time information about their location, speed and acceleration amongst others with their neighboring equipped vehicles. This opportunity of information sharing can be exploited to allow cooperate adaptive cruise control (CACC) wherein vehicles come together as “intentional platoons” to move at similar speeds and maintain closer gaps with the front vehicle. We use the micro-simulation software VISSIM to model this behavior and assess its impacts. The following sections discuss the background and the modeling process in detail.

7.1.1 Introduction to CACC Platoons

Cooperative adaptive cruise control (CACC) is an extension of adaptive cruise control (ACC) where the latter relies on sensor-based technology to detect motion changes in the preceding vehicle and adjusts the vehicle’s speed accordingly (FHWA, n.d.). While ACC provides benefits over traditional cruise control, the time lag induced due to sensor-based detection is significant to allow other vehicles to cut in. Also, ACC systems, like traditional human driving, may not exhibit string instability, i.e., due to higher response time, fluctuations in traffic flow induced by accelerating and braking of vehicles can be amplified upstream, resulting in phantom traffic jams. CACC systems, on the other hand, have been shown to overcome this limitation by adding V2V communication to ACC (Shladover, Nowakowski, Lu, & Ferlis, 2015; Milanés et al., 2014). Thus, CACC equipped vehicles can get information from similarly equipped vehicles ahead of them downstream and use this information to make decisions related to their own speed and acceleration. The term “cooperative” indicates that vehicles can come together to agree to information transfer amongst themselves such that they can synchronize their speeds and acceleration to avoid sudden jerks. CACC also enables vehicles to move closer to each other as response times are reduced due to V2V communication. These properties of CACC enabled vehicles allow them to move together as groups in the form of “platoons.”

Traditionally, a platoon has been viewed as a group of vehicles following each other at similar speeds. While this following may be intentional, this behavior only involves the follower’s decision to trail behind the preceding vehicle. With CACC, this phenomenon can be intentionally introduced with similarly equipped vehicles agreeing to move close together and sharing information about the leader (the front most vehicle in the platoon). The communicated information is in the form of basic safety messages (BSM) which includes information about a vehicle’s location, speed, acceleration, etc. (SAE International, 2016a). Using this information about the leader’s motion changes, following platoon members can better prepare themselves for situations downstream, which results in string stability. Moreover, closer gaps between platoon members reduces air drag and thus, fuel consumption. In fact, two-truck platoons have shown fuel savings up to 10% in the rear truck and 4.5% in the front truck (leader) (Taylor, Allen, & Shaver, 2018). To compensate for lesser savings, the platoon members can agree to provide some incentives (such as monetary benefits) to the leader vehicle (Shladover et al., 2015; Brännström, 2013). Figure 7.1 provides a visual representation of a platoon of three cars.

In this study, we use the constant-time-gap strategy to define platoons (Shladover et al., 2015). This means that a platoon member follows its predecessor in the platoon (if any) at reduced and constant time gaps. Time gap between a vehicle and its predecessor is defined as the time (in seconds) elapsed between passing of the rear bumper of the predecessor and the front bumper of the vehicle at a fixed location on the roadway. Therefore, the spacing between successive vehicles

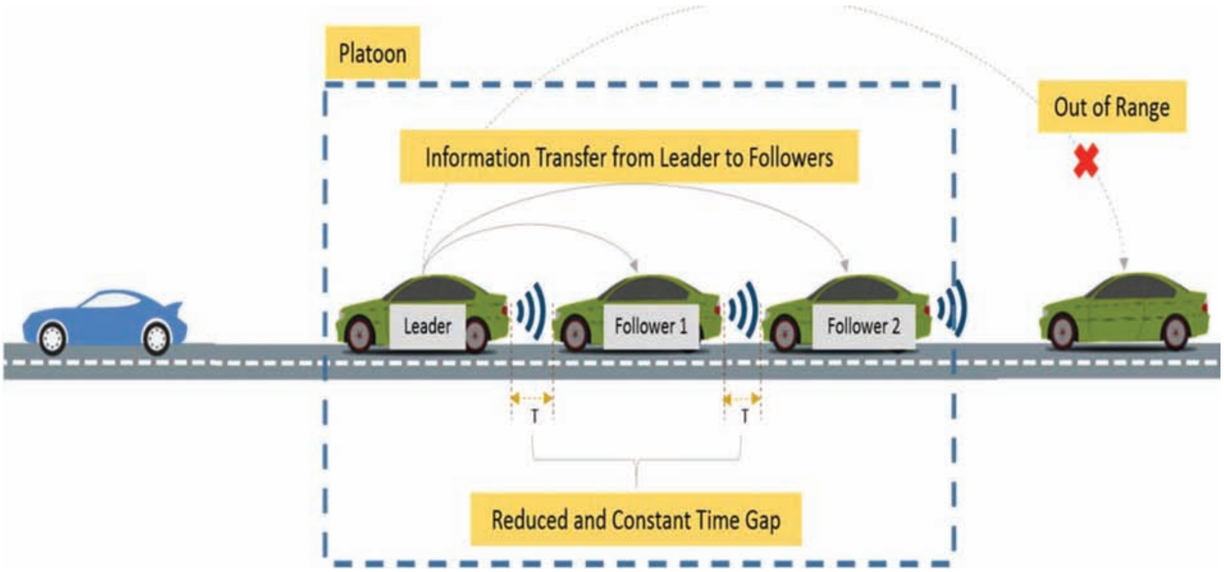


Figure 7.1 A platoon of three cars.

may vary depending on their speeds, but they try to maintain a constant time gap.

The modeling approach of CACC platoons adopted in this study is discussed in the following sections.

7.1.2 Modeling CACC Platoons

We use the External Driver Model API of the microsimulation software VISSIM to allow platooning of vehicles. We model ad-hoc platooning wherein vehicles platoon as and when they find opportunities in their present state. Therefore, vehicles are not instructed to change lanes or wait at on-ramps for potential platooning opportunities.

This section is split into three parts. First, we describe the algorithm for platoon formation, followed by the car following models used to model the behavior of different vehicle types. The third part highlights the assumptions and limitations of the modeling approach.

7.1.2.1 Platoon Formation. When a CACC-enabled vehicle enters the network, it starts searching for platooning opportunities with other CACC-enabled vehicles. When it detects a CACC-enabled vehicle within a certain distance in front of it, it checks with it for platooning opportunities. We set this searching threshold as 100 m, which is directly adopted from (Songchitruksa, Bibeka, Lin, & Zhang, 2016).

If the predecessor is a platoon member itself, it checks with the maximum allowed platoon to see if platoon formation is allowed. The maximum platoon size is usually limited to 10 in literature (Songchitruksa et al., 2016; Li et al., 2017). We test with no restriction on the maximum size so as observe the maximum sized platoon that can be formed in this ad-hoc setting.

If the predecessor is not a platoon member, a two-membered platoon is formed, provided the predecessor is not about to change lanes or make a turn. The whole process is described as a flowchart in Figure 7.2. The behavior of a vehicle once it enters a platoon is discussed in the subsequent sections.

7.1.2.2 Car-Following Models. At a broad level, we consider two types of vehicles in the system—CV and non-CV. Since CACC would require at least system's control over acceleration and braking, CACC-equipped vehicles correspond to SAE Level 1 of automation (Shladover et al., 2015). Thus, we consider the base case of non-CVs as SAE Level 1 vehicles. CVs also follow the same car-following models as non-CVs until they join a platoon. When a CV joins a platoon, it can either be the leader or a follower. The leader of a platoon is the front-most vehicle, which leads the platoon. Rest of the members are followers. The leader behaves like a non-CV, except the fact that it transmits its location, speed and acceleration to the followers and lets them follow at closer distances. However, follower vehicles behave differently and have a modified car following model, which is discussed subsequently. The hierarchical classification discussed above is shown in Figure 7.3.

7.1.2.2.1 Non-Platooning Vehicles. As discussed above, non-CVs and non-platooning CVs follow the same car-following models as SAE Level 1. We use enhanced IDM to model SAE Level 1 as discussed in section 6.1.2.2. Here, we take the value of coolness factor (c) as 0.99.

7.1.2.2.2 Platooning Vehicles. The leader vehicle has no platoon member preceding it and hence, can only use adaptive cruise control (ACC). Therefore, we use enhanced IDM to model the leader's behavior no differently than non-platooning vehicles.

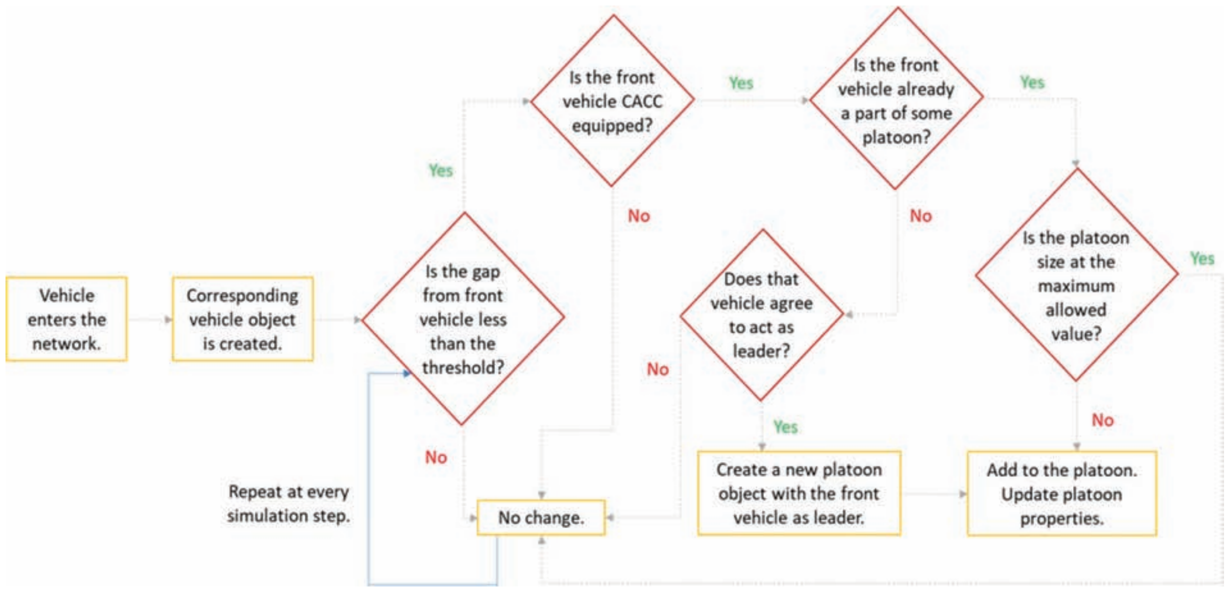


Figure 7.2 Platooning algorithm for CACC-equipped vehicles.

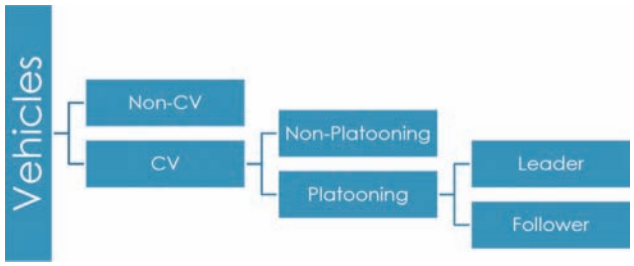


Figure 7.3 Classification hierarchy of vehicles.

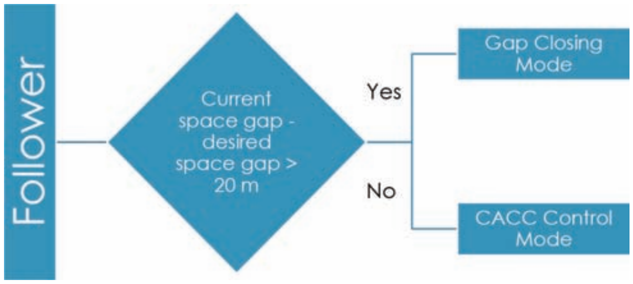


Figure 7.4 Platooning states of follower.

On the other hand, a follower can use CACC and thus, behaves differently as compared to other vehicle types. Furthermore, we use different models depending on the state of platooning that a follower is in. The states are described in Figure 7.4. Space gap is defined as the distance to the vehicle's front bumper from the predecessor's rear bumper. Desired space gap is calculated based on desired time gap and current speed of the vehicle.

When the follower is in gap closing mode, we use the car-following model used by Songchitruksa et al. (2016), which is as follows:

$$v_e = v - v_d \qquad \text{(Eq. 7.1)}$$

$$a_{sc} = bound(-0.4v_e, 2, -2) \qquad \text{(Eq. 7.2)}$$

$$s_d = T_d.v \qquad \text{(Eq. 7.3)}$$

$$s_e = s - s_d \qquad \text{(Eq. 7.4)}$$

$$a = bound(\dot{s} + 0.25s_e, a_{sc}, -2) \qquad \text{(Eq. 7.5)}$$

where:

v = speed of the controlled vehicle (m/s)
v_d = desired speed set by driver or speed limit of the road (m/s)
v_e = speed error (m/s)
a_{sc} = acceleration by speed control (m/s^2)
s = space gap between controlled vehicle and its predecessor (m)
s_d= desired space gap (m)
T_d = desired time gap (s)
$bound(a,b,c)$ = max(min(a,b),c)

When the difference between current space gap and desired space gap drops below 20 m, the follower switches to CACC control mode where the behavior is described by the model proposed by Li et al. (2017):

$$a_n(t + t_d) = a_{acc} + \lambda_1 a_1(t) + \lambda_{n-1} a_{n-1}(t) \qquad \text{(Eq. 7.6)}$$

where:

t = time (s)
t_d= delay in information transfer from leader to the controlled vehicle (s)
a_n= acceleration of the vehicle in the platoon, $n \neq 1$
a_{acc} = acceleration of the n^{th} vehicle calculated using enhanced IDM (m/s^2)

a_1 = acceleration of the platoon's leader (m/s^2)
a_{n-1} = acceleration of the immediate predecessor in platoon (m/s^2)
λ_1, λ_{n-1} = weighting coefficients

Assuming that information transfer from a vehicle to its immediate successor takes one simulation time-step, i.e., 0.1 s, we take t_d=0.1(n–1) as the delay from the leader to the n^{th} vehicle.

Weighting coefficients λ_1, and λ_{n-1} are taken as 0.3, as adopted from Li et al. (2017).

7.1.2.3 Assumptions and Limitations of the Model. Since the interaction of CVs and non-CVs is complex enough, there are several inherent assumptions in the modeling approach that we follow. The assumptions are listed below.

1. We consider a traffic stream with passenger cars only. While trucks also have the potential to platoon, the interaction between CACC-enabled cars and CACC-enabled trucks is complex (Shladover et al., 2015) and was therefore excluded from the study. A cars-only scenario also allows us to evaluate platooning opportunities between connected cars, especially when all cars are CACC equipped.
2. We assume ad-hoc formation of platoons. This means that vehicles are not guided to change lanes or wait at on-ramps to avail themselves of platooning opportunities. If CACC-equipped vehicles happen to be traveling successively in the same lane, only then can they platoon. However, we do allow vehicles to speed up in order to close the gap with the predecessor, in case they are far away. Other types of platoon formation—local and global coordination—allow vehicles to deviate from their current lanes and/or routes to gain additional platooning opportunities. Local coordination is when vehicles are guided to change lanes, if necessary, and avail local platooning opportunities nearby, outside of their immediate neighborhood on the road. On the other hand, global coordination involves planning of such platooning opportunities in advance. Vehicles traveling between similar origins and destinations can be matched to form a platoon from the start of their travel. Local and global coordination were not considered in our modeling owing to the complexity involved in assessing opportunities beyond immediate neighborhood of the controlled vehicle and providing accurate maneuvering directions to reach the potential target. More discussion on challenges with local and global coordination can be found in Shladover et al. (2015).
3. A platoon is only allowed to grow in the upstream direction. This means that that a CACC-equipped vehicle can only join an existing platoon at its rear, provided the platoon does not grow beyond the maximum allowed size. This also means that two or more existing platoons do not merge to form one big platoon.
4. We restrict the lane-changing maneuvers of platoons. This assumption is in line with Songchitruksa et al. (2016) where this restriction is justified to promote longevity of the platoon. However, if a platoon member needs to make a mandatory lane change, it exits the platoon and leaves. The original platoon may just reduce in size or split into two platoons depending on the position of the exiting member in the original platoon.
5. If a vehicle wants to change lanes and has to cut into an existing platoon, the platoon splits appropriately to allow this maneuver. However, to ensure that the platoon stays intact longer, only mandatory lane changes are allowed by the platoon.

7.2 Experimental Design

7.2.1 Network Description

The test network is a two-lane freeway corridor approximately 1.7 miles (2.7 km) long. The test network was designed to facilitate the following:

1. Investigation of Platoon Evolution
   Since we follow ad-hoc platooning technique, we intended to investigate how CACC-equipped vehicles evolve to form platoons. This required a sufficiently long corridor with uninterrupted flow to allow opportunities for vehicles to come together.
2. Longevity of Platoons
   According to our platooning model, platoons break if a vehicle needs to mandatorily cut into the platoon or leave the platoon. This affects the longevity of platoons, which is directly related to the benefits they provide.

Figure 7.5 shows the test network. We can two platoons in the figure. Red-colored vehicles are the platoon leaders while green-colored vehicles are followers. The blue-colored vehicle is a CACC-equipped vehicle in non-platooning status. On can also see a large gap between the second and third member of platoon 1. This is because the third member is in gap control mode and is trying to close the gap with its predecessor.

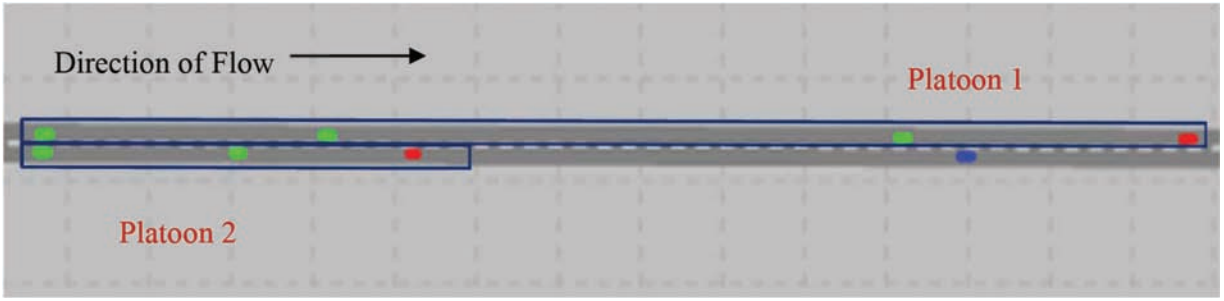


Figure 7.5 Test corridor for evaluating platoon formation.

7.2.2 Simulation Settings

Now, we discuss the simulation settings that were adopted for this study.

7.2.2.1 Desired Time Gap. We define three gap-choosing strategies—low, medium and high. Every vehicle entering the network is assigned a strategy, which stays with it throughout the simulation. This assumption is based on the intuition that a conservative driver will always choose a higher time gap with higher probability, while an aggressive driver will do the opposite. Each gap strategy corresponds to a different multinomial distribution for the same set of desired time gaps. First, all vehicles choose from the desired time gaps corresponding to ACC. We allow four values—1.1, 1.5, 1.7 and 2.2 s—which are adapted from previous studies (Nowakowski et al., 2011; Jones, 2013). When a vehicle joins a platoon as a follower, it is assigned a new desired time gap based on sampling from the set corresponding to CACC—0.6, 0.7, 0.9 and 1.1 s. The desired time gap values and their distributions are adapted from Nowakowski et al. (2011). A new time gap is assigned from the ACC set if this vehicle leaves the platoon at some point. It again becomes evident that assigning a gap strategy beforehand assures that an aggressive driver always has a higher probability of choosing a lower gap at each transition. The distributions adopted for this study are listed in Table 7.1 and Table 7.2

7.2.2.2 Vehicle Characteristics. All vehicles are cars and have similar dimensions. However, separate vehicle classes for CV and non-CV vehicles were created so as link each type to a different External Driver Model DLL file. We also controlled vehicle colors for visual evaluation of platoon formation. The colors are listed in Table 7.3.

TABLE 7.1
Multinomial Distribution for Gap Strategy

Gap Strategy	Low	Medium	High
Probability	0.5	0.3	0.2

TABLE 7.2
Multinomial Distribution for Time Gap Based on Gap Strategy

ACC Time Gaps (s)		1.1	1.5	1.7	2.2
CACC Time Gaps (s)		0.6	0.7	0.9	1.1
Probability	Low	0.5	0.25	0.15	0.1
	Medium	0.2	0.3	0.3	0.2
	High	0.1	0.15	0.25	0.5

TABLE 7.3
Vehicle Colors Based on Type and Status

Vehicle color	Black	Blue	Red	Green
Vehicle status	Unequipped	CACC-equipped in non-platooning status	Platoon Leader	Follower in a platoon

7.2.2.3 Corridor Characteristics. The corridor is modeled as a two-lane freeway approximately 1.7 miles long. The desired speed is set at 55 mph (90 km/h). We test for two flow rates—800 veh/h/lane and 400 veh/h/lane. Although the corridor is straight, we allow vehicles a choice of two destinations—through or right turn. VISSIM automatically assigns a vehicle to its destination in the ratio 3:2, which was set by us. We also set the look ahead distance for CVs as 500 m so that they know of mandatory lanes changes 500 m ahead. The VISSIM default is 200 m, which was increased to 500 m assuming CVs get this information wirelessly. The value is not derived from industry experiments, but was chosen based on the range of communication technology (such as DSRC) that can transmit upcoming network information to CVs downstream.

7.3 Impact Analysis

We now present the simulation results from our test corridor. First, we discuss the characteristics of platoons. Then, we discuss the mobility impacts of platooning.

7.3.1 Platoon Formation

In this section, we explore the formation and evolution of a platoon in an ad-hoc formation setting.

7.3.1.1 Trajectory of a Platoon. Figure 7.6 is a plot of the time-space diagram of a platoon, which could attain maximum size 12. Different colors represent different vehicle trajectories. Jerks in vehicle trajectory represents change in platoon. Diverging trajectories represent breaking of platoon while merging trajectories indicate platoon expansion.

Let us evaluate the three snapshots shown in the plot. Snapshot 1 represents the situation when vehicles have just entered the network. We see higher spacing between vehicles initially. Snapshot 2 represents the case when the vehicles have spent some time in the network and have had the opportunity to platoon. Thus, we see vehicle trajectories closer to each other than snapshot 1. Snapshot 3 is when the vehicles are leaving the network. Therefore, platoons break, and we see that trajectories diverge. We also see some vehicles still moving close to each other. This maybe because they were going to the same destination and did not have to break apart.

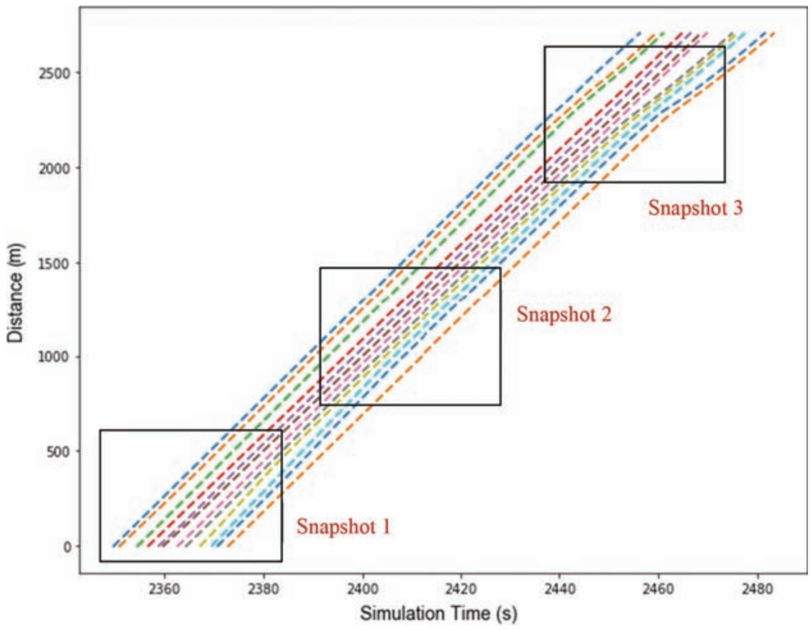


Figure 7.6 Time space diagram of a platoon.

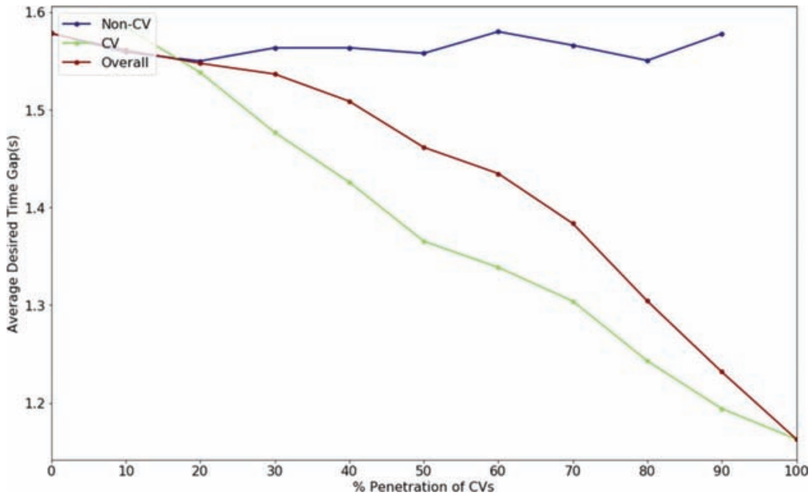


Figure 7.7 Variation of average desired time gap with different penetration levels.

7.3.1.2 Desired Time Gap. Figure 7.7 shows the variation of desired time gap with different penetration levels for flow rate of 800 veh/h/lane. The desired time gap is stochastically chosen as discussed in section 7.2.2.1. We observe that as the percentage of CVs in the traffic composition increases, the overall average time gap between vehicles in the network keeps decreasing. This is so because with more CVs, more platoons are formed which move at closer time gaps as compared to non-CV vehicles. The average time gap of non-CV vehicles is almost the same since they cannot platoon.

7.3.1.3 Number of Platoons. Figure 7.8 shows the number of platoons formed in the simulation. As expected, the number of platoons formed is higher with higher percentage composition of CVs. In addition, higher flow rate implies higher number of platoons are formed since the chance of vehicles being within 100 m of each other is higher for higher flow rate. Interestingly, at higher penetration levels, the slope of the curve is increasing for lower flow rates while it is almost constant for higher flow. We can infer from here that when the chance of platooning is low (whether due to low penetration or low flow), a slight increase in number of CVs would have a higher increase in the number of platoons as compared to when the flow rate and saturation are high.

7.3.1.4 Platoon Size. Figure 7.9 illustrates the variation of platoon sizes with saturation of CVs and flow rate. Lighter color implies that the platoon size is more frequent. We see that the most common platoon size is two

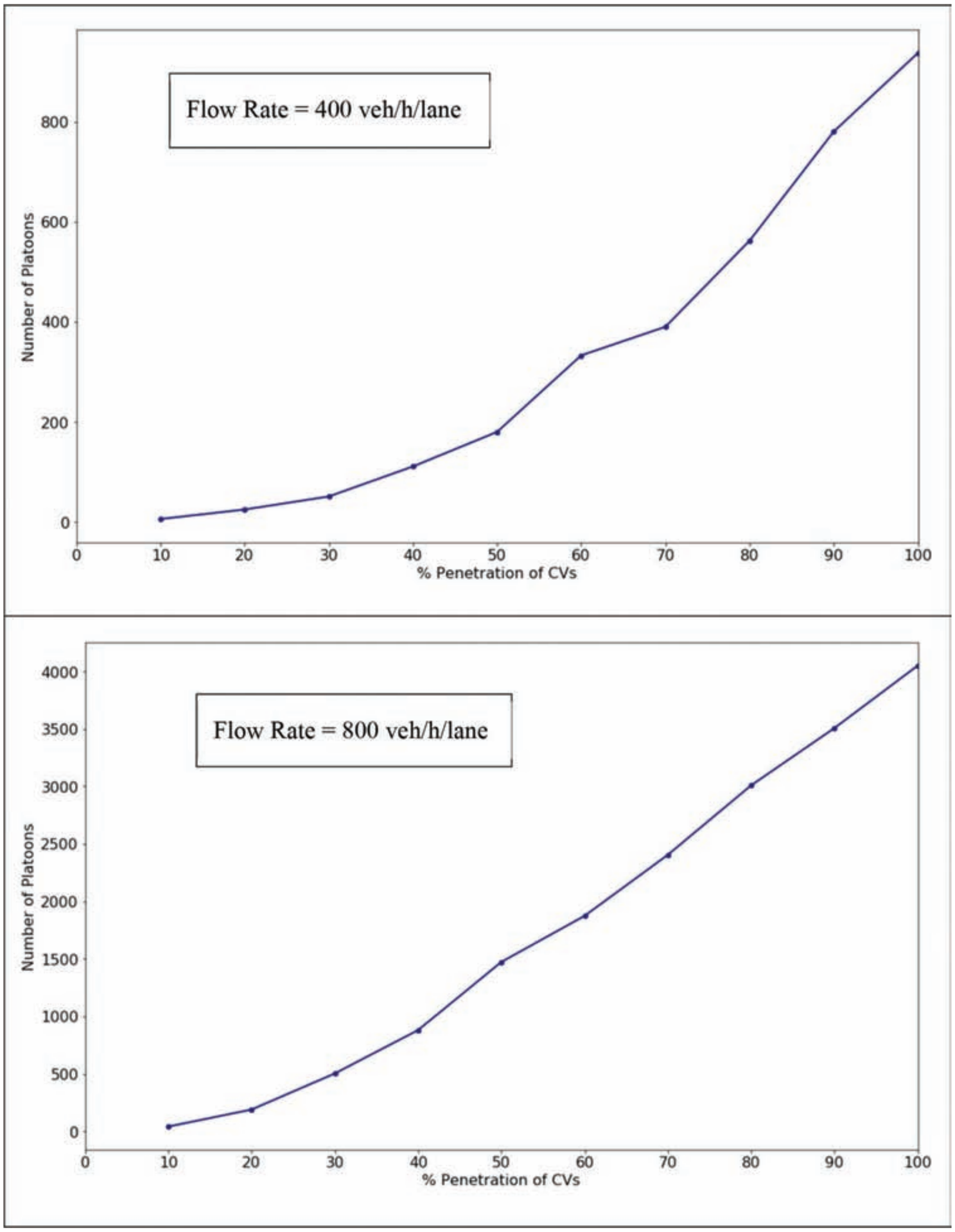


Figure 7.8 Number of platoons formed at different saturation levels of CVs at different flow rates.

for both the flow rates, especially when more CVs are present. This observation can be attributed to our assumption that platoons grow only at the rear. At higher penetration, the chances of two vehicles being near each other are higher and thus, the chance of platoons being formed is higher. Also, higher concentration of CVs implies that the chance of two vehicles coming together to form two-sized platoons at the same time is higher. Since we do not allow two small platoons to merge and form one big platoon, size 2 remains dominant in the system.

We also observe that the maximum platoon size, which can be, achieved increases with increase in both flow and CV concentration. When the system is fully saturated with CVs, the maximum platoon size that is observed with 400veh/h/lane is eight while that with 800 veh/h/lane is 13. Interestingly, this maximum corresponds to 90% penetration of CVs for flow of 800 veh/h/lane as opposed to 400 veh/h/lane where the maximum is obtained at 100% CVs. This suggests that as flow rate increase, the maximum platoon size that can be achieved occurs at a penetration level lower than 100% penetration since the chance of small platoons being formed increases with higher percentage of CVs.

7.3.2 Impact Assessment

Now we discuss the impacts of platooning on average travel time and average speed in the network.

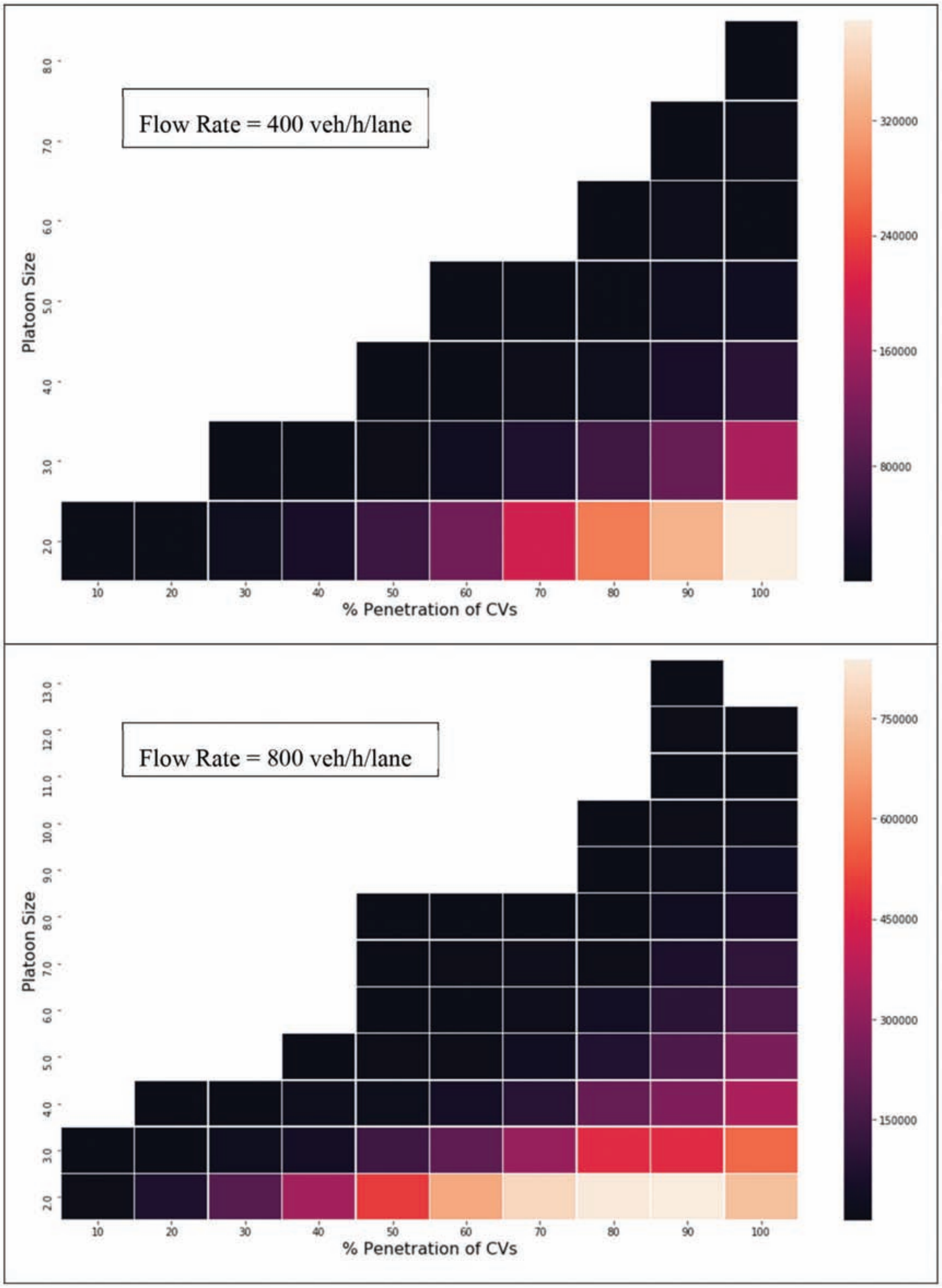


Figure 7.9 Variation of platoon size with different compositions of CVs.

7.3.2.1 Average Travel Time. Figure 7.10 shows the variation of average network travel time with different flow and penetration. We observe a 3% decrease in average travel time with 100% CACC equipped vehicles as compared to 0%, when the flow rate is 800 veh/h/lane. With a flow rate of 400 veh/h/lane, about 1% decrease in average travel time is observed. At a flow rate of 800 veh/h/lane, the average travel time at 50% penetration

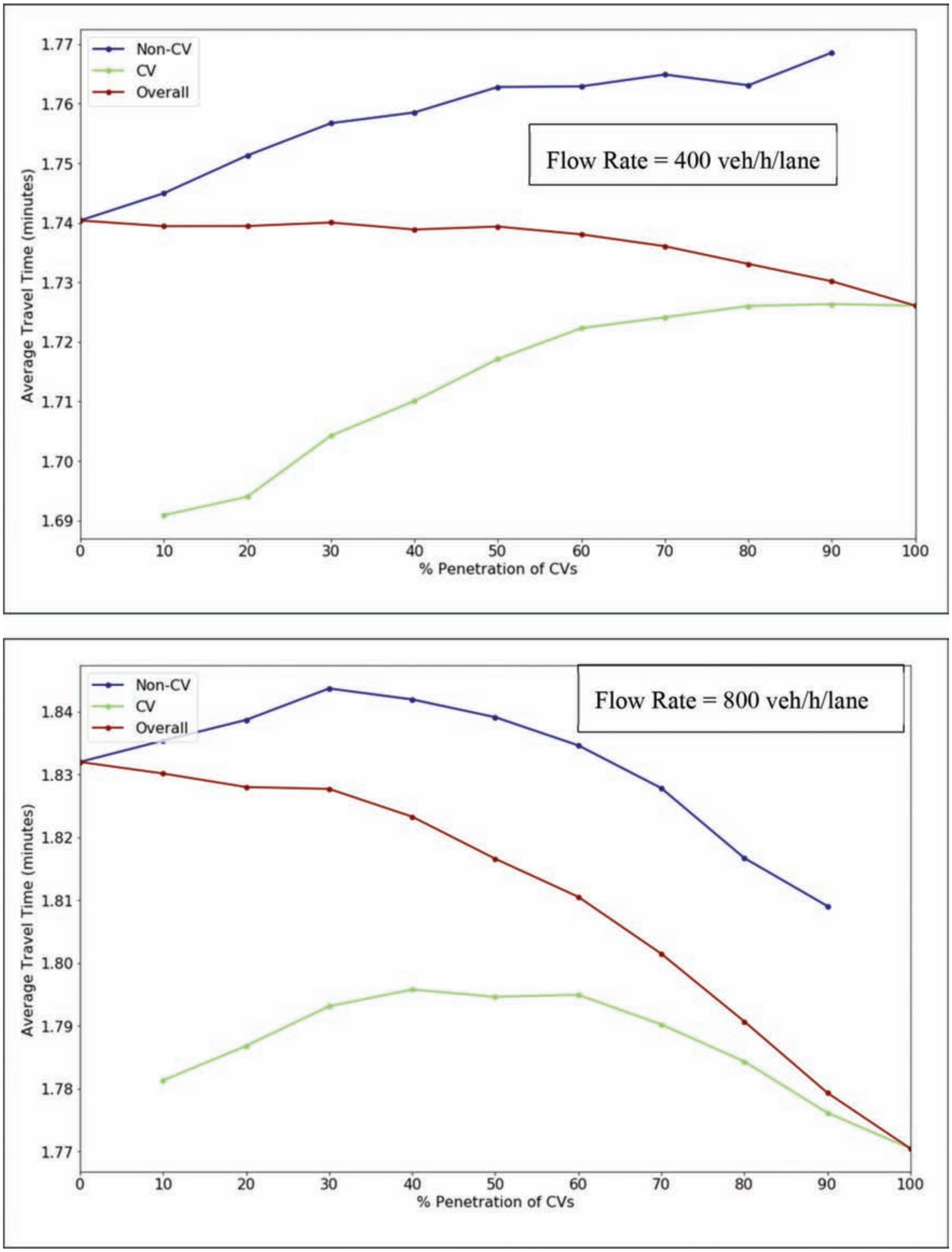


Figure 7.10 Variation of average travel time with different penetration rates of CVs.

decreases by only 0.5%. However, we observe steeper decrease in average travel time at higher percentages. This implies that a certain saturation of CVs would be needed before benefits seem significant. Improvements may not seem significant with the test corridor, but are expected to accumulate over a network.

7.3.2.2 Average Speed. Figure 7.11 describes the variation of average speed in the network with different CV composition and flow rate. We see improvements in average speed with higher CV composition. However, the improvement is marginal when the flow rate is 400 veh/h/lane. On the other hand, we observe

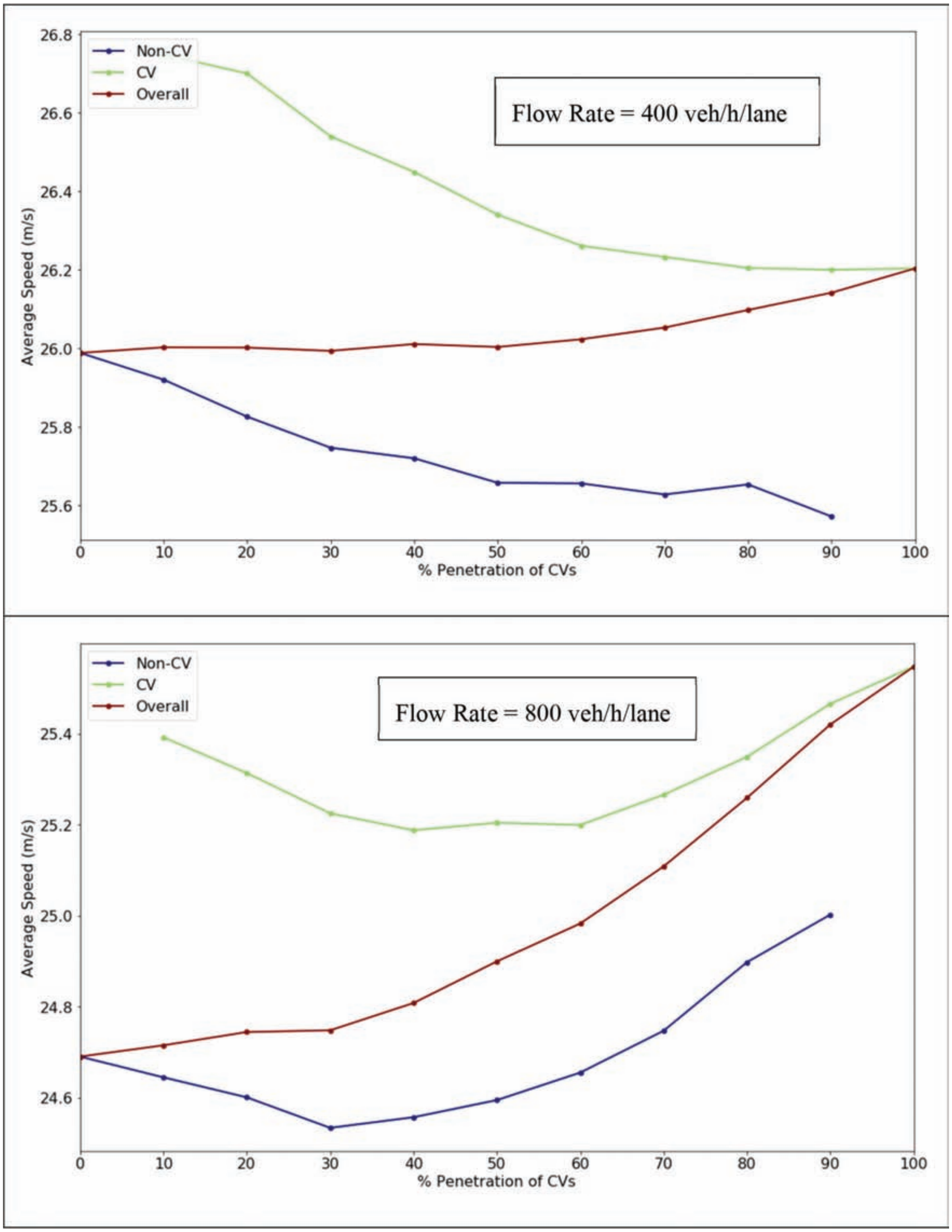


Figure 7.11 Variation of average speed with different CV composition.

1% and 3% increase in average speed with 50% and 100% saturation respectively when flow rate is 800 veh/h/lane. We also see that the speed of non-CV vehicles drops significantly with higher saturation of CVs when flow rate is lower. Therefore, platooning of CACC-enabled vehicles negatively affects unequipped vehicles when flow is low or penetration of CVs is low.

8. SIGNAL CONTROL WITH CONNECTED VEHICLES

With the advent of connectivity, a breakthrough in traffic management is expected. Communication capabilities among vehicles and infrastructure have the potential to provide more accurate real-time information about the network that would have been inaccessible otherwise. This information can be leveraged to upgrade and/or redesign current traffic control devices such as traffic signals for better performance. This chapter discusses changes in signal control policies and operation with the introduction of connectivity.

8.1 Expected Benefits with Connectivity

Infrastructure such as traffic signals can communicate via three main ways—vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V) and infrastructure-to-infrastructure (I2I) communications. V2I communication allows connected vehicles to send basic safety messages (BSM) to the signal controller several times per second when they are within a certain range of the controller (SAE International, 2016a). If dedicated short-range communication (DSRC) is the mode of communication, this range can be 1 km for non-line-of-sight applications (Kenny, 2011; SAE International, 2016a). With 5G, the range will be higher. This means that the controller has access to CVs' data up to 1 km or more in all directions, which is significantly higher as compared to the typical 15–50 m range for detector-based control (Klein, Mills, & Gibson, 2006). However, the challenge is to store and manage such a large amount of data without infringing upon the privacy of the vehicle and then process it to arrive at a signal control decision in real-time. The ways in which CV data can be utilized are discussed in section 8.2.

Once relevant information has been extracted from the CV data, an optimal signal control decision can be made. While the decision can be at the level of an isolated intersection, I2I communication between different signal controllers can help to arrive at an optimal strategy from the network's perspective. Potential signal control policies leveraging connectivity are discussed in section 8.3.

Further, once the decision is made, the information about current and upcoming signal phase and timing can be broadcast to all CVs downstream via I2V technology. This allows vehicles to react to signal changes proactively and adjust their speed accordingly. Optimal speed to traverse the intersection can also be broadcast so that vehicles move at harmonized speeds, thereby increasing throughput (FHWA, 2014). A major advantage of this broadcast is elimination of the dilemma zone, where drivers are uncertain if they should stop or proceed when approaching a signalized intersection (Misener, Shladover, & Dickey, 2010). Thus, mobility and safety improvements can be expected at intersections due to connectivity (ITS JPO, n.d.g). In fact, Chang et al. (2015) have shown the effectiveness of different combinations of V2I applications at signalized intersections in prioritizing signal timing and reducing delay by up to 27%. Their results also show that CACC and speed harmonization can reduce travel time on freeways by up to 42%.

8.2 Utilizing Connected Vehicle Data

As per SAE Standard J2735, vehicles capable of V2I can send basic information about their location, speed, acceleration, turning movement, etc., in a basic message format to the signal controller. No personally identifiable information is shared for security and privacy reasons. This message can be sent several times per second until the vehicle is within the controllers' range. This means that the controller has access to spatiotemporal information about the CVs approaching the intersection, unlike detector-based vehicle data, which is only point information about the vehicles when they run over the detector. Thus, several limitations of detector-based vehicle detection are overcome by V2I communication.

The first-hand usage of CV data is as a replacement of detector-based data. A detector's accuracy is limited by the length up to which it is installed, while V2I communication allows vehicles to communicate with the controller even in non-line-of-sight conditions. If all vehicles are connected and transmit a BSM, performance metrics such as queue length, than vehicle delays, etc., can be measured exactly. However, with a heterogeneous mix of connected and non-connected vehicles, these metrics cannot be exactly determined but rather estimated from the CV data due to unknown states of unequipped vehicles. This problem has been widely studied in literature and researchers have developed different algorithms to estimate trajectories of non-connected vehicles from trajectories of connected vehicles. Zhu and Ukkusuri (2017) proposed an Expectation-Maximization (EM) technique based on Kalman filtering approach to estimate the state of non-connected vehicles. Feng, Head, Khoshmagham, & Zamanipour (2015) also developed an algorithm called Estimation of Vehicle Location and Speed (EVLS) to estimate speed and location of unequipped vehicles by segregating the space near the intersection into different regions based on speed and acceleration characteristics of approaching vehicles. Other studies based on vehicle trajectory estimation using mobile sensor data also find potential in estimating the missing trajectories.

Another information that CVs are capable of storing and communicating is the accumulated delay they have encountered over their trip in the network. This information can be used to give priority to an already delayed vehicle to minimize overall delay in the network from the system's perspective. Aziz and Ukkusuri (2016) proposed a signal control algorithm named Fair Queueing (FQ) that takes into account this notion of fairness to a delayed road user while optimizing the system's performance.

Besides direct performance metrics, BSMs sent by CVs also contain information about their turning movements. This information can be used to accurately estimate demand with respect to different turning movements. When coupled with trajectory estimation, accurate information about demand of each turning movement can potentially be leveraged to arrive at real-time optimal coupling of phases. This also prevents false activation of a phase when a right turning vehicle arrives at an intersection with free right turn.

However, as discussed earlier, less than 100% saturation of CVs poses a challenge to relying on CV data only due to the absence of unequipped vehicles' information. While this can be addressed to some extent by using algorithms which estimate the missing trajectories, low penetration of CVs (less than 10-20%) can affect the accuracy of such estimations (Feng et al., 2015). Thus, it has been suggested in literature that detectors be used in conjunction with CV data during the initial transition phase. Several algorithms take this into account in their formulation.

8.3 Signal Control Policies in the CV Context

The availability of detailed and accurate CV data in real-time opens up opportunities to employ both already existing policies with more accurate data or new signal control policies utilizing information unavailable with traditional detector-data. An immediate application is adaptive signal control, policies for which are already available for detectors and sensors-based approach such as SCOOT, ACS-Lite, RHODES, etc. However, due to the expenditure involved in installing and maintaining detectors that can collect the required high-resolution data, these policies have not been widely implemented in practice. With connectivity and especially 5G technology for wireless communication, these infrastructure-related costs are expected to go down (Feng et al., 2015), which opens the possibility of employing these polices at a wider scale.

However, CV data is much richer than detector-data in that the former provides a vehicle's entire trajectory in the vicinity of the signal. Several researchers have studied the potential uses of this data and developed signal control especially in the CV context. These policies utilize V2I communication data with I2I capabilities at times to optimize the signal controllers' performance either at an isolated intersection's level or for network wide control. We summarize some relevant policies in Table 8.1.

Besides signal control policies using CV data, the idea of "autonomous" intersections with connectivity has also emerged, where V2V, V2I and I2I together facilitate safe maneuver of vehicles through the intersection. First introduced by Dresner and Stone in 2008, an autonomous intersection was proposed as a multi-agent system which uses a reservation-based approach using a communication framework between vehicles and infrastructure (Dresner & Stone, 2008; VanMiddlesworth, Dresner, & Stone, 2008). Several other works have expanded upon this idea (Huang, Sadek, & Zhao, 2012; Carlino, Boyles, & Stone, 2013; Zhu & Ukkusuri, 2015).

8.4 Simulation Framework to Evaluate Benefits

In the previous section, we discussed signal control policies that can be used in a CV setting. With connected vehicle technology still being in the testing stage until date, one can only test and compare their relative performance either by in-field testing of each policy at a test corridor or by using a simulation-based approach. The former option is difficult to implement because certain policies assume high penetration rate of CVs and fully matured CV technology capable of providing high-definition data. Thus, a simulation-based approach seems reasonable and feasible to test and compare the benefits and performance metrics of the new policies proposed in literature. In this section, we investigate the feasibility of using the micro-simulation software VISSIM to evaluate the policies and provide a framework that can be used to do the same.

As per the official documentation, VISSIM is capable of testing adaptive signal control with a detector-based approach. Yet, a connected environment with V2X and I2X cannot be directly implemented as such. However, VISSIM does allow three APIs, which can be used to make external changes to its internal model—External Driver Model API, Signal Control API and Component Object Model (COM) Interface. External Driver Model API allows us to use our own models to describe a vehicle's behavior—car-following, lane-centering and lane-changing. This API was used in the previous two chapters to model different SAE levels of autonomous vehicles and platooning behavior of CACC-equipped vehicles. Thus, V2V communication can be simulated using this API. Along similar lines, Signal Control API allows implementation of our own signal control policy. However, the utility of this application is limited by the fact that vehicle data can only be collected using a detector-based approach. Thus, this API alone cannot be used to evaluate benefits with connectivity. COM Interface, on the other hand, not only allows automation of simulation runs from an external script but also data retrieval at each simulation time-step. Moreover, one can also change signal phases directly based on own signal policy. Therefore, we choose COM to simulate communications with the infrastructure, which is the signal controller in our case. In addition, COM operates with an external script and we choose Python as the scripting language in our framework.

Now, the first requirement of signal control with CVs is the capability of a signal controller (SC) to save information about the vehicles approaching it. Investigating further into VISSIM and COM both, we realize that we can only access the collective information of vehicles at the level of a link. However, certain signal control policies, such as those involving network wide control, need aggregate metrics at the intersection level. Therefore, we propose a hierarchical approach to link different elements in the network with the introduction

TABLE 8.1
New Signal Control Policies Utilizing CV Data

Authors (year)	Algorithm	Description
Priemer and Friedrich (2009)	Decentralized adaptive traffic signal control algorithm with V2I communication data	Phase based algorithm which minimizes queue length using dynamic programming.
He, Head, and Ding (2012)	Multi-modal signal control algorithm with pseudo-platoons in a V2I communication environment	Identifies pseudo-platoons in the network using headway. MILP formulation using priority requests.
Goodall, Smith, and Park (2013)	Predictive microscopic simulation algorithm (PMSA) for signal control	Uses microsimulation to predict future from CV data. Computationally intensive and cannot be implemented in real-time.
Christofa, Argote, and Skabardonis (2013)	Signal control strategy to limit and prevent queue-spillbacks detected using CV technology	Detects queue spillbacks using CV data based on two approaches—geometric distribution of arrival of unequipped vehicles and kinetic wave theory of traffic.
Feng, Head, Khoshmagham, and Zamanipour (2015)	Two-level optimization-based phase allocation algorithm using CV data	Arrival table constructed using estimation of vehicle location and speed (EVLS) algorithm. Two-level optimization solved using dynamic programming.
Zhu, Aziz, Qian, and Ukkusuri (2015)	Junction tree-based reinforcement learning algorithm optimizing network-wide signal control using V2I and I2I communication	Learning-based signal control algorithm for coordination among signals at the network level with queue length as reward. Can be used for cyclic and acyclic networks.
Zeng, Sun, Zhang, and Quadrifoglio (2015)	Person-based adaptive priority signal control with CV information	Computes individual vehicle delay from CV data, thus avoiding explicit assumptions about vehicle arrivals. Computes person delay with on-board passenger information. Objective is to minimize person delay.
Aziz and Ukkusuri (2016)	Fair queuing algorithm for signal control accounting for user level fairness in terms of trip delay	Uses a modified expectation maximization approach with Kalman filtering on a customized state-space model.
Day et al. (2017)	Detector-free approach to signal coordination by optimizing offsets using CV data	"Virtual Detection" generates arrival profiles of vehicles using CV data that can be used to optimize offsets for signal coordination.
Beak, Head, and Feng (2017)	Adaptive coordination-based signal control to provide progression to vehicles	Bi-level optimization approach. Upper level is the intersection level, which allocates green phase using dynamic programming based on coordination constraints. Lower level is the corridor level that uses MILP to optimize offsets.
Feng, Zheng, and Liu (2018)	Real-time detector free adaptive signal control with low penetration of CVs	Dynamic programming-based approach, which uses estimated delay as the performance function. In the absence of CV data during one cycle, historic traffic data is used to make the decision. Improved performance than actuated control under 10% CV penetration.

of an intersection object. The hierarchy is illustrated in Figure 8.1. An intersection object is linked to a unique signal controller in VISSIM. Likewise, a signal phase corresponds to a unique signal group and a lane has a unique signal head. Furthermore, an intersection has multiple signal phases where each phase is defined as another object in the formulation. Similarly, a phase has multiple links associated with it and a link has multiple lanes. We assume that each link corresponds to only one phase. However, a phase may allow multiple movement directions, for example through and right turn.

This hierarchy starting with an intersection object is effective in obtaining intersection metrics using bottom-up approach. For instance, Zhu et al. (2015) use queue length at an intersection as a metric to decide the optimal signal phase at each intersection to optimize the overall throughput of a network comprising of multiple intersections. Using the proposed object hierarchy, we can first find the queue length at each lane using

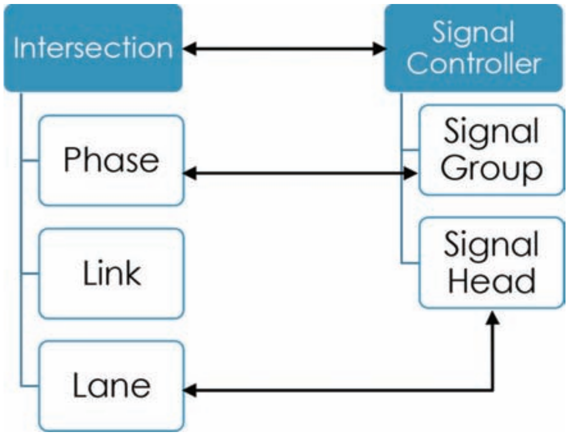


Figure 8.1 Hierarchical representation of new simulation objects in COM.

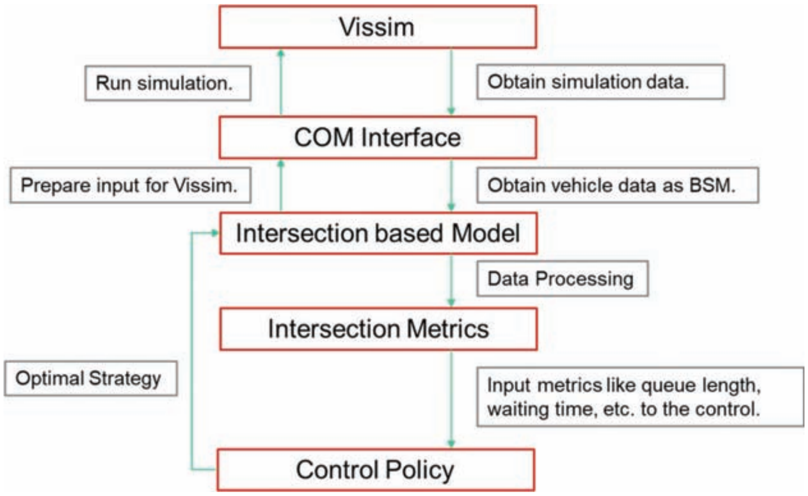


Figure 8.2 Framework to simulate signal control policies in the CV context.

the stored CV data and then, keep summing up the queue length at each object level starting from a lane to the intersection. Furthermore, any other variant, which may use queue length of a link or even the aggregate queue length of a phase, can be easily incorporated using this formulation.

With the above object hierarchy at the backdrop, VISSIM can be used to implement signal control algorithms that use CV data. Figure 8.2 shows diagrammatically how this can be accomplished.

8.5 Expected Changes, Challenges, and Recommendations

From the discussion so far, one can observe that signal control policies in the context of CVs is a well-researched topic and researchers have not only proposed control algorithms for the same but also possible solutions to deal with low penetration of CVs initially. With this being in place, the main holdback to realization of connectivity at present is the ongoing debate of whether to use dedicated short-range communication (DSRC) or cellular vehicle-to-everything (C-V2X) for communication amongst vehicles and infrastructure (Cain, 2018; Wassom, 2018; Woyke, 2018).

While DSRC has been well tested and is mature for deployment, it requires a huge infrastructure investment that may take some time to become possible. C-V2X, on the other hand, relies on the current cellular infrastructure, but needs to be tested for stability before being fully rolled out (Cain, 2018; Nigro, 2018). NHTSA's pending mandate on proposed rulemaking about DSRC further adds to the uncertainty of which technology to invest in. This is, thus, a major challenge to CV deployment at present.

However, after the approved 3GPP Release 14 in June 2017, C-V2X is promised to be tested, validated and commercially available by 2020 (5GAA, 2018). While supporters of DSRC want to invest in it head on, proponents of C-V2X indicate that given the infrastructure investment that DSRC requires, its deployment timeline cannot be expected to be sooner than C-V2X (Cain, 2018; Nigro, 2018). Amidst this debate, several others argue that both the technologies would complement each other rather than compete in the connected future (Grossman, 2018; Wassom, 2018).

Considering the uncertainty in how the connected future would shape and which technology would emerge to be viable, we recommend the following to INDOT:

1. Since the debate is still on, it is advisable not to make huge infrastructure investments in either of the technologies. However, investment in DSRC and/or C-V2X testbeds should be considered. Colorado Department of Transportation is investing in both DSRC and 5G, since both technologies seek to improve road safety (Leonard M., 2017; Marek, 2018; Woyke, 2018). A similar venture would be an opportunity for INDOT to be actively engaged in the process, and be aware of the pros and cons of both the technologies. We would recommend INDOT to test both these technologies—DSRC and C-V2X—on one of their test corridors. Same test corridors are recommended for both, so that implementation costs, benefits and challenges can be compared across both the technologies without any bias due to different testing locations.
2. Using the simulation framework suggested above, signal control policies of interest can be tested on networks of choice. This would help INDOT prepare for a CV future in the meantime.

9. CONCLUSIONS

This study looks at modeling and analysis of performance aspects of autonomous and connected vehicles.

Autonomous vehicles are modeled as SAE Levels 0, 1, 2, 3, 4 and 5 using a bottom-up modeling approach. This is a first of its kind approach to AV research. Together, the modeling of SAE Levels 0, 1, 2, 3, 4 and 5 indicates that AV features, are capable of yielding significant benefits from the standpoints of safety and mobility. We also studied the mobility impacts on traffic for various mixes of SAE levels. The results show interesting patterns for the various penetration tested. This validates the applicability of AVs to infrastructure systems through confirming the magnitude of their positive impacts on safety and mobility.

In order to evaluate the safety impacts of AVs, we have defined SAE specific thresholds, which are then used to evaluate the risky conflicts that occur in the simulations for each SAE level. These thresholds are tested on a 3 by 3 signalized grid and the conflicts are identified after the AV trajectory is analyzed in SSAM. We observe that based on the thresholds defined, the conflicts reduce significantly as the AV have more accurate maneuvering capacity and more acute sensing of the environment.

Connected vehicles are defined as vehicles capable of V2V communication and equipped with CACC functionality. Based on this, we model intentional platooning of CVs using an ad-hoc platoon formation algorithm. Based on simulations on the test corridor, we observe that CV platoons provide benefits in terms of travel time and speed. We also see that a certain minimum percentage composition of CVs should be present for these benefits to emerge fully.

Next, we review signal control policies in the CV context and identify changes expected in this domain. We also develop a VISSIM based framework using which any of the signal control algorithms can be implemented and tested in a simulation setting.

This work will be an asset for practitioners, policymakers and researchers to perform capacity analysis and highway design as the connected and autonomous future becomes a reality. The model can accommodate different mixes of traffic. With this work as a foundation, extensions of future work can be in multiple areas. Research divisions at OEMs can assess the mobility impacts of autonomous vehicles by calibrating the AV model with their design specifications. Our model can also be used as a platform to integrate new ADAS features and evaluate their impact on traffic. Using the platooning framework, benefits with platooning of different vehicle types can be assessed. The simulation framework for signal control provides yet another useful tool to implement and test new signal control policies which employ CV data.

9.1 Key Findings

Here, we summarize the key findings from the study along with their implications.

9.1.1 Mobility Impacts of AVs

1. Starting SAE Level 1, the system takes control over acceleration and braking. We observe that with 100% penetration of SAE Level 1, average speeds near merging sections increase by 3% in comparison to SAE Level 0. Interestingly, about 40% of this increase can be achieved with just 20% SAE Level 1 and 80% SAE Level 0. Thus, significant increase in mobility can be expected even with percentages as low as 20% of SAE Level 1 and above.
2. SAE Level 2 onwards, system's control over lane centering is introduced. We observe that the average standard deviation of vehicles' lateral deviation can drop down by 50% when transitioning from SAE Level 1 to SAE Level 2. With SAE Level 4, the decrease can be up to 87% as compared to SAE Level 1. This decrease in the tendency of AVs to deviate from the center of the lane can be utilized to potentially decrease lane-widths in an AV only traffic scenario.
3. From SAE Level 3, the system also takes control of lane changing operations. Since the autonomous system can be assumed to detect lane-changing opportunities better, we introduce a lower threshold acceleration for lane change to occur when the vehicle is in system's control as opposed to human control. We observe that while the number of lane changes in SAE Level 3 increase by 300% as compared to SAE Level 2, the impacts on mobility are insignificant (around 0.3% increase in average speed as compared to SAE Level 2).
4. SAE Level 4 is fully autonomous in its operational design domain (ODD). When outside ODD, the AV tries to achieve a minimal risk condition. We model this minimal risk condition as lowering of speeds to minimal risk condition design speed (MRCDS) (30 mph). The outside ODD condition is modeled as unclear pavement markings on the roadways. We observe that as compared to SAE Level 5, which is fully autonomous under all situations, the drop in average speed with SAE Level 4 is almost 50%. In fact, even in traffic conditions with 20% SAE Level 4 and 80% SAE Level 5, the average speed is 30% lesser than a fully SAE Level 5 stream. Therefore, outside ODD conditions (such as unclear pavement markings) significantly affect the mobility with SAE Level 4.
5. We conduct a traffic volume analysis for the I-70 and I-465 freeway interchange with full saturation of different SAE levels. We see that due to the reduction in headway across the SAE levels, the volume throughput can increase significantly. The volume throughput of SAE Level 1 is 33% more than that of SAE 0. Similarly, the throughput of SAE Level 5 is about 2.5 times that of SAE 0. This can result in significant increases in the road capacity.

9.1.2 Safety Impacts of AVS

Surrogate measures of safety can be used to assess the mobility impacts of different SAE levels from a simulation experiment. We use time to collision (TTC) as the measure and introduce different and reduced TTC thresholds for different SAE levels. From SAE Level 0 to SAE Level 1, due to reduction in threshold TTC, the conflicts reduced by over 30%. Furthermore, from SAE Level 0 to SAE Level 5, the conflicts reduce to one-tenth of the conflicts in SAE Level 0. Thus, we see an increase in safety with higher SAE levels, despite lower headways.

9.1.3 Impacts of Platooning with CVS

1. We model intentional platooning of vehicles with CACC capability such that each equipped vehicle seeks for platooning opportunities with other equipped vehicles within 100 m range. Platooned vehicles then move at closer headways and use the acceleration information of the leader vehicle to make decisions related to their own acceleration. We test impacts for different traffic compositions of CACC equipped vehicles.
2. We observe a 3% decrease in average travel time with 100% CACC equipped vehicles as compared to 0%, when the flow rate is 800 veh/h/lane. With a flow rate of 400 veh/h/lane, about 1% decrease in average travel time is observed. Thus, we can say that benefits of platooning materialize with higher flow rates.
3. At flow rate of 800 veh/h/lane, the average travel time at 50% penetration decreases by only 0.5%. However, we observe steeper decrease in average travel time at higher percentages. Similarly, we observe 1% and 3% increase in average speed with 50% and 100% saturation respectively. This suggests that a certain percentage (50% in our case) is required for benefits to emerge with platooning. This may warrant for introducing dedicated lanes for platoon formation when CACC penetration is 50% or less.
4. We observe that the most common platoon size is two, but platoons of sizes as high as 13 are also observed for 90% penetration and above. This calls for modifications in present traffic management techniques to allow for smooth movement of large groups of vehicles moving together.

9.1.4 Signal Control with CVS

1. We conducted a literature review on signal control with CVs and found that a combination of V2I, I2I and I2V communication can help increase performance at the network level. Several new algorithms have been developed by Prof. Ukkusuri (Zhu & Ukkusuri, 2017; Aziz & Ukkusuri, 2016; Zhu et al., 2015; Aziz, Zhu, & Ukkusuri, 2017) and other researchers which employ this information and show improved performance as compared to traditional detector-based signal control.
2. We also developed a framework to simulate connectivity and identify the different features in traditional versus CV-based signal control. Any algorithm of interest to INDOT can be fully integrated and tested in a future project using this framework.

9.2 Future Extensions

Possible extensions in the next few years based on this study include:

9.2.1 SAE Level Testing Extensions

1. Impacts of AV only lanes for Trucks/Cars
2. Impacts on Mobility and Safety with a Mix of Autonomous Vehicle Classes (Cars and Trucks)
3. Impacts of Inconsistent/Unclear Pavement Markings on AV Functionality
4. Impacts of Non-Standardized Signs on AV Performance
5. Assessment of Infrastructure Needs and Possible Changes for AVs (Similar research has been carried out by Texas DOT (Kockelman et al., 2017).)
6. Impact Assessment of AVs using Scaled-Down Testing Approach with Integration of BARC Project (see Gonzales, Zhang, Li, & Borrelli (2016) and https://www.barc-project.com/ for details.)
7. Assessment of AV Performance from an AV Test-Bed in Indiana

9.2.2 Safety Extensions

1. Impacts of Autonomous Intersections
2. Assessment of Surrogate Safety Measures for AVs

9.2.3 CV Extensions

1. Mobility and Safety Impacts of Truck Only Platooning
2. Impacts of Dedicated Lane for Platoons
3. New Signal Control Algorithm at Isolated Level
4. New Signal Control Algorithm for Network Wide Control
5. Assessment of CV Performance with SPaT Messages

Note: For all CV projects, potentially use data from the US 31 project.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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About This Report

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Recommended Citation

Ukkusuri, S., Sagir, F., Mahajan, N., Bowman, B., & Sharma, S. (2019). *Strategic and tactical guidance for the connected and autonomous vehicle future* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/02). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316879