RESEARCH & DEVELOPMENT

Plan for Advanced Technology Data Readiness

Srinivas S. Pulugurtha, Ph.D., P.E., F.ASCE, The University of North Carolina at Charlotte (UNC Charlotte)

Ninad Gore, Ph.D., UNC Charlotte

Dil Samina Diba, B.S., UNC Charlotte

Chirag Akbari, M.Tech., UNC Charlotte

Elizabeth Shay, Ph.D. AICP, Appalachian State University

Richard Crepeau, Ph.D., Appalachian State University

Thanh Schado, B.S., Appalachian State University

NCDOT Project TCE 2020-01

FHWA/NC/2020-60

July 2023

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/NC/2020-60		

4. Title and Subtitle
Plan for Advanced Technology Data Readiness

5. Report Date
July 31, 2023

6. Performing Organization Code

7. Author(s)
Srinivas S. Pulugurtha, Ph.D., P.E., F.ASCE; Ninad Gore, Ph.D.; Dil Samina Diba, B.S.; Chirag Akbari, M.Tech.; Elizabeth Shay, Ph.D. AICP; Richard Crepeau, Ph.D.; Thanh Schado, B.S.

8. Performing Organization Report No.

9. Performing Organization Name and Address
The University of North Carolina at Charlotte
9201 University City Blvd
Charlotte, NC 28223-0001

10. Work Unit No.

11. Contract or Grant No.
FHWA/NC/2020-60

12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Development Unit
1020 Birch Ridge Drive
Raleigh, NC 27610

13. Type of Report and Period Covered
Final Report (February 2020 to July 2023)

14. Sponsoring Agency Code

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

16. Abstract
Advanced transportation technologies, such as connected and automated vehicles (CAVs), have the potential to revolutionize the transportation industry by improving safety, traffic efficiency, and mobility. However, integrating CAVs also brings unique challenges in managing the vast data they generate. Public agencies, like the North Carolina Department of Transportation (NCDOT), play a crucial role in handling CAV-related data tasks, including crash analysis, vehicle registration, tracking, and revenue management. Furthermore, introducing CAVs requires understanding the new data requirements for infrastructure, land use, and the built environment. This study summarizes best practices for CAV data collection and tracking, captures and analyzes the perception of practitioners and industry experts, and recommends a novel data readiness framework based on the results. The proposed data readiness framework sets priorities for stakeholders, such as the NCDOT, in formulating policies and upgrading infrastructure for a CAV-inclusive transportation environment.

17. Key Words	18. Distribution Statement
Connected and automated vehicles (CAVs), data readiness framework	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	68	

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

DISCLAIMER

The contents of this report reflect the views of the author(s) and not necessarily the views of the University. The author(s) are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

Acknowledgments

The authors express their sincere thanks and gratitude to the transportation professionals who participated in the focused group meetings. Transportation system users who participated in the survey are also acknowledged. Moreover, the inputs from practitioners and industry experts through the survey are also greatly appreciated.

Raghavan Srinivasan, Nancy Lefler, Nitesh Shah, Wesley Kumfer, and Taha Saleem from the University of North Carolina at Chapel Hill Highway Safety Research Center (HSRC) are acknowledged for participating in the brainstorming sessions. The inputs from these professionals helped formulate and modify the data readiness framework.

Table of Contents

List of Figures

List of Tables

Executive Summary

Advanced transportation technologies, such as connected and automated vehicles (CAVs), have the potential to revolutionize the transportation industry by improving safety, traffic efficiency, and mobility. However, integrating CAVs also brings unique challenges in managing the vast data they generate. Public agencies, like the North Carolina Department of Transportation (NCDOT), play a crucial role in handling CAV-related data tasks, including crash analysis, vehicle registration, tracking, and revenue management. Furthermore, introducing CAVs requires understanding the new data requirements for infrastructure, land use, and the built environment. The project aims to develop an NCDOT-specific framework for data readiness, identifying CAV-specific data requirements and mapping them to public agency use cases. This framework will support the prioritization of CAV deployment and ensure the safe operation of CAVs in North Carolina.

A comprehensive literature review was conducted to explore the various aspects and implications of CAVs. Technological advancements, consumer preferences, and the efforts of government and non-governmental organizations were analyzed to understand the progress and potential of CAVs. The review highlighted the benefits of CAVs, including enhanced safety, traffic efficiency, and increased accessibility. The challenges related to infrastructure readiness, vehicle data safety, public acceptance, cost and benefits, traffic control and operation, land use, transportation demand, long-range transportation plans, and laws and policies were also identified.

Infrastructure readiness is crucial for deploying CAVs, emphasizing road design, signage, and traffic signal optimization considerations. Vehicle-related data emerged as a critical concern, requiring collaboration between manufacturers and policymakers to address cybersecurity risks and ensure privacy. Public acceptance of CAVs depends on consumer trust, awareness, and understanding. The review also emphasized the importance of considering land use implications, transportation demand, long-range planning, and appropriate policies to facilitate CAV integration.

Focus group discussions were conducted with transportation professionals in North Carolina to gather insights into their perceptions, opinions, and concerns regarding CAVs. The focus group discussions explored data requirements, privacy and security, and the potential impacts on transportation, land use, safety, and security. The analysis of information gathered through the focus group discussions revealed that transportation professionals are interested in CAV discussions but are uncertain about specific actions and reliable sources of information. Clear technical guidance and materials for community engagement are recommended. The discussions also revealed relative ambivalence among young adults, challenging assumptions about their high interest in CAVs. Further research is needed to understand public attitudes and their implications for CAV development.

A seven-month open survey using the online platform "Qualtrics" was conducted to capture the perceptions of practitioners and industry experts related to various aspects of CAVs. Twenty-two responses from practitioners and industry experts were collected and analyzed. The findings suggest that practitioners and industry experts perceive the impact of CAVs on safety, operations, mobility, parking, and urban sprawl differently. Moreover, the perception of the infrastructural and policy-related changes needed differs between practitioners and industry experts. Overall, the results revealed the need to update traffic control devices, provide

dedicated lanes for CAVs, and restrict CAVs in areas with higher densities of pedestrians and bicyclists. Proactive efforts from transportation authorities are necessary to address concerns about data requirements, personal safety and security, and regulatory and policy development.

A data readiness framework focusing on four categories: vehicle, infrastructure, data, and public impression is proposed. Specific action items and recommendations are provided for each category. These include exploring advanced vehicle registration methods, periodic testing of vehicle features, updating infrastructure to accommodate CAV needs, establishing data standards and privacy protocols, and conducting staff education and public awareness programs. The framework will guide different North Carolina agencies, enabling effective CAV data management and seamless integration into the transportation system.

The proposed data readiness framework and implementation plan aim to create an integrated and inclusive CAV environment in North Carolina. The findings from the literature review, focus group meetings, and perception surveys provide valuable insights into the challenges and opportunities associated with CAV data readiness. By developing a framework that addresses the unique data requirements of CAVs and aligning them with public agency use cases, NCDOT can effectively manage and leverage CAV-related data for prioritizing deployment, ensuring safety, and maximizing the benefits of CAV technology for transportation customers in North Carolina.

1. Introduction

The rapid advancement of transportation technologies has paved the way for connected and automated vehicles (CAVs), offering numerous benefits to transportation customers. CAVs represent a fusion of automation and connectivity. These innovative vehicles have the potential to enhance road safety, improve traffic efficiency, and revolutionize the overall mobility experience. However, alongside these advancements come unique challenges, particularly in managing the data generated by CAVs.

CAVs utilize advanced communication technologies that enable interaction with other vehicles (V2V) and with the transportation infrastructure (V2I) (Dey et al., 2016). The V2V communication, position, speed, and direction related data facilitate predictive decision-making to avoid potential collisions, optimize traffic flow, and enhance overall transportation efficiency. Complementarily, V2I communication broadens the communication domain of CAVs beyond other vehicles to the surrounding infrastructure. This technology involves exchanging information with traffic signals, signs, roadwork alerts, and other infrastructure elements. V2V and V2I are essential for ensuring seamless and safer operations of CAVs.

The Society of Automotive Engineers (SAE) defines CAVs in six levels starting from Level 0, "no automation," where the human driver executes all driving tasks, even when supplemented by warning or intervention systems (SAE, 2021). Level 1, "driver assistance," involves vehicles with a single automated feature for tasks such as steering or acceleration (SAE, 2021). Level 2, or "partial automation," enables the vehicle to control both steering and acceleration/deceleration, albeit with constant monitoring by the human driver (SAE, 2021). At Level 3, "conditional automation," vehicles can manage all aspects of the driving tasks. However, the human driver will intervene when requested (SAE, 2021). Level 4, "high automation," vehicles can handle all driving tasks without human intervention, but this capability is limited to certain conditions and environments (SAE, 2021). Lastly, Level 5, "full automation," represents vehicles capable of performing all driving tasks under all conditions that could be handled by a human driver (SAE, 2021).

The efficient analysis, utilization, and integration of data play a crucial role in enabling the seamless and safe operation of CAVs and ensuring their successful deployment. Public agencies like the North Carolina Department of Transportation (NCDOT) must handle various data-specific tasks, including crash analysis, vehicle registration, tracking, and revenue management. Moreover, there is a growing need to understand the data requirements related to land use and the built environment as CAVs interact with the transportation infrastructure.

1.1 Problem Statement and Goals

The advent of CAVs brings numerous benefits for transportation customers. However, it also introduces complexities in handling data-related tasks such as crash analysis, vehicle registration, tracking, and revenue management. Furthermore, it is pivotal to understand these novel data requirements concerning land use and the built environment due to the unique requirements of CAVs on infrastructure. Therefore, it is crucial to identify how the data requirements for CAVs differ from those of traditional vehicles to prepare for their deployment.

The goal of this proposed effort is to develop an NCDOT-specific framework for data readiness by

1. identifying the CAV-specific data public agencies need, and,
2. mapping the data to public agency use cases.

Because “data” is a broad term, the CAV data are discussed in four categories: vehicle, infrastructure, crash, and public impression.

This study summarizes best practices for CAV data collection and tracking, captures and analyzes the perception of practitioners and industry experts, and recommends a novel data readiness framework based on the results. The proposed data readiness framework sets priorities for stakeholders, such as the NCDOT, in formulating policies and upgrading infrastructure for a CAV-inclusive transportation environment. The data readiness framework can be shared with the North Carolina Fully Autonomous Vehicle Committee’s (FAVC) Operations Working Group.

1.2 Organization of the Report

The remainder of the report consists of five chapters. Chapter 2 comprehensively discusses and summarizes the effect of CAVs and the best practices adopted to accommodate the impacts of CAVs. Chapter 3 introduces the research methodology adopted in this study. Chapter 4 comprehensively discusses the results related to the focus group meetings. The results of the perception of practitioners and industry experts on various aspects related to CAVs are comprehensively discussed in Chapter 5. A data readiness framework is proposed and summarized in Chapter 6 as an essential practical outcome and recommendation. The implementation and technology transfer plan is illustrated in Chapter 7.

2. Literature Review

The progress of CAVs is primarily influenced by technological advancements, consumer preferences, and the efforts of government and non-governmental organizations (Underwood et al., 2014; Litman, 2023). CAVs will revolutionize the transportation industry in terms of operations, safety, infrastructure, and economics. Optimistic forecasts propose that fully automated vehicles could become prevalent between 2025 and 2035 (Benkraouda and Chakraborty, 2022). The predictions rely on the development of numerous technologies, such as real-time map updating, wireless software updates, localization techniques, and the enhancement of V2V and V2I communication (Fagnant and Kockelman, 2015; Anderson et al., 2016; Payalan and Guvensan, 2019). However, the rate of technological advancements and their eventual realization in the widespread deployment of CAVs remains to be determined and is contingent on factors like cost, feasibility, reliability, and standardization (Benkraouda and Chakraborty, 2022).

2.1 Infrastructure

Studies reveal that infrastructure readiness is generally considered the most crucial aspect. At the same time, stakeholder groups differ in their opinions on policy and regulation readiness, possibly due to their varied expectations regarding the impacts of CAVs (Jiang et al., 2022). Tengilimoglu et al. (2023) found thirteen critical features related to infrastructure, including road design, cross-section elements, shoulders, road surface structure, road markings and signs, intersections, bridges and tunnels, vulnerable road users, speed limits, road drainage systems, road lighting, and asset and maintenance strategies, that should be considered either during the initial phase of deployment or during the transition to full automation (Tengilimoglu et al., 2023).

Technological advancement is significant as it influences consumer trust and acceptance and allows cities to implement infrastructure changes. Key technologies like 5G, 3D printing, and infrastructure digitalization are essential for CAV acceptance (Benkraouda and Chakraborty, 2022). Research revealed underserved areas with connectivity issues, particularly at intersections with heavy traffic, and identified that localization accuracy was affected in dense areas with buildings and trees (Cucor et al., 2022). Prioritizing infrastructure preparations is crucial to ensure the successful reception of CAVs and minimize risks such as malware infection or cyberattacks (Vassallo and Manaugh, 2018). Moreover, to support CAVs, physical infrastructure elements like signage, wayfinding boards, lane markings, and pavements should be updated and marked for successful detection by CAVs (Faisal et al., 2019). Specific signs and markings may need to be updated to accommodate CAV technology, and intersections and traffic signals should transition to innovative applications with adjusted locations and timing (Faisal et al., 2019). Utilizing existing infrastructure by assigning high-occupancy vehicle lanes exclusively to CAVs can optimize network performance and energy consumption (Benkraouda and Chakraborty, 2022). Infrastructure investment is essential for creating a CAV-friendly environment and ensuring the successful integration of autonomous fleets (Vassallo and Manaugh, 2018). It includes infrastructure elements, such as signage, lane markings, and data/communications to facilitate V2I and V2V communication (Cohen and Cavoli, 2019).

2.2 Vehicle Data Safety

CAV-related privacy and cybersecurity risks have received significant attention. However, environmental and employment risks have been less studied. Some governments have started worker retraining programs (Lim and Taeihagh, 2018). Cyberattacks or software faults could lead to crashes, privacy violations, and other unforeseen consequences. Such attacks could also breach privacy and security thresholds by accessing susceptible data (Lim and Taeihagh, 2018).

The security and privacy-related vulnerabilities of CAVs make them the weakest link in the slicing chain, enabling attackers to compromise slice isolation and degrade network performance. The cross-border nature of slicing introduces additional security risks that must be addressed for reliable and secure 5G-V2X slicing deployments (Boualouache et al., 2023). Researchers examined the issue of spatially clustered CAV malware and its potential impact on urban geographies of inequity, highlighting how malware can spread through V2X networks and cluster in specific linguistic, socioeconomic, and political enclaves of cities, resulting in new geographies of accessibility, mobility, economic, and environmental inequities (Vassallo and Manaugh, 2018). The role of subnational transportation planners in mitigating these inequities through malware prevention measures and discussing the need for further research on regulation, planning, and shared vehicle provisioning about CAV cybersecurity is necessary (Vassallo and Manaugh, 2018).

The reliance on data transfer and connectivity makes CAVs susceptible to cyber-attacks, necessitating collaboration between manufacturers and policymakers to address these issues (Lim et al., 2023). The Cybersecurity Regulatory Framework (CRF) should involve all stakeholders and focus on leverage points such as automakers' innovation, risk sharing, and utilizing CAV-generated data (Khan et al., 2022).

2.3 Transportation System Users

With technological advancements, it is crucial to comprehend the consumer acceptance of CAV technology and how it impacts its deployment. Researchers found a significant gap between public interest in CAVs and policy support, emphasizing the importance of the readiness index for policymakers to enhance policies and infrastructure for CAV integration (Khan et al., 2019).

Predicting acceptance rates can be challenging, considering the uncertainties and potential vulnerabilities associated with CAVs (Benkraouda and Chakraborty, 2022). However, it is also vital to acknowledge the varying cultural and contextual differences that may exist from one region to another. The adoption of CAVs in specific areas largely depends on the acceptance and willingness of residents to use and own these vehicles (Benkraouda and Chakraborty, 2022; Nodjomian and Kockelman, 2019). Optimism, insecurity, and previous experience with CAVs significantly influence intentions to use a conditional automated vehicle (O'Hern and Louis, 2023). Consumer preferences also significantly influence the adoption of CAVs. Variables such as demographic characteristics, job accessibility, residential location, and consumer trust and awareness can significantly impact the acceptance and adoption rate of CAVs (Duarte and Ratti, 2018; Lim and Taeihagh, 2018; Stoiber et al., 2019; Burghard and Dütschke, 2019; Nodjomian and Kockelman, 2019; Zhang et al., 2019). However, predicting the adoption rates and mapping the future layout of CAVs remains a significant challenge for planning agencies due to significant variations in demographic and socio-economic factors across different regions (Benkraouda and Chakraborty, 2022).

Nodjomian and Kockelman (2019) suggest that suburban residents are more inclined toward CAV usage than city dwellers. Conversely, those commuting to densely populated or urbanized areas exhibit higher acceptance for shared autonomous vehicles (SAVs) (Benkraouda and Chakraborty, 2022). Dense urban areas are projected to attract more SAVs, while single-use developments are expected to witness the introduction of CAVs before multi-use areas (Duarte and Ratti, 2018; Nodjomian and Kockelman, 2019).

Demographic factors greatly influence the acceptance and potential use of CAVs. Men are more inclined towards owning or utilizing an automated vehicle, with considerations such as residential location and commute times playing a role (Nodjomian and Kockelman, 2019). Younger individuals are more open to CAVs, and car ownership influences the type of CAV a consumer is likely to adopt. Notably, lower-income individuals or those relying heavily on public transportation are likelier to use SAVs (Burghard and Dütschke, 2019). The equity implications of CAVs are uncertain, with potential benefits for non-drivers but possible negative impacts on low-income communities if public transportation services are reduced (Vassallo and Manaugh, 2018).

CAVs allow drivers to undertake other activities during travel, further enhancing user benefits (Szimba and Hartmann, 2020; Anderson et al., 2016). However, CAVs are expected to impact jobs primarily involving driving, leading to redundancies and concerns about job loss. Economic shifts are also expected, with job losses in specific sectors such as taxi services but potential gains in the construction and information technology services sectors (Faisal et al., 2019; Pettigrew et al., 2019).

Public awareness and understanding of these changes is limited. A survey in Australia and interviews with stakeholders worldwide highlighted the need for labor market planning due to the inevitable widespread adoption of CAVs, the potential effects on non-driving occupations, and the potential for improved worker safety and commuting opportunities (Pettigrew et al., 2019).

2.4 Cost and Benefits

CAVs can operate optimally to reduce fuel consumption, become more cost-effective, and contribute significantly to environmental conservation efforts (Anderson et al., 2016). Despite having higher operating costs, CAVs deliver significant user benefits through time savings and non-driving activity time, estimated at 1,310–2,240 € per annum for Level 4 and 2,770–3,440 € per annum for Level 5 vehicles, thereby reducing overall costs of motorized mobility and potentially making urban outskirts more attractive as living areas (Szimba and Hartmann, 2020). Cost-effectiveness is a significant predictor of CAV adoption, particularly for SAVs. Competitive pricing with other transportation modes may prompt users to overcome privacy concerns and perceived inconvenience (Anderson et al., 2016). Fagnant and Kockelman (2015) showed that the substantial social benefits, including crash savings, travel time reduction, fuel efficiency, and parking advantages, could reach nearly $4000 per CAV per year.

2.5 Safety and Trust

Consumer trust and awareness are crucial for CAV acceptance. Understanding CAV capabilities, benefits, and limitations increases the willingness to adopt the technology (Benkraouda and Chakraborty, 2022). However, trust remains a challenge that needs to be addressed, with cybersecurity advances, proven physical safety, perceived ease of use, and usefulness expected to increase public acceptance (Lim and Taeihagh, 2018; Zhang et al., 2019).

Various scholars have taken the initiative to investigate the diverse categories of technological risks associated with CAVs. These encompass safety, privacy, and cybersecurity concerns (Lim and Taeihagh, 2018). CAV technology brings with it an array of benefits that can drastically improve the transportation system. One of the most significant advantages is the potential reduction in vehicle crashes. As human error is eliminated from the driving equation, a substantial decrease in crashes, leading to safer roads for all users, is anticipated (Anderson et al., 2016). Previous research highlights the contribution of advanced driver assistance systems (ADAS) towards safer, more efficient, and more comfortable trips (Payalan and Guvensan, 2019). CAVs could increase safety and efficiency but induce more travel due to lower costs and time saved, causing an energy rebound effect (Taiebat et al., 2019).

2.6 Mobility and Accessibility

CAVs can reduce vehicle ownership, traffic congestion, and travel costs while increasing accessibility and revenue generation (Rahman and Thill, 2023). CAV technology stands to enhance the mobility of several demographic groups. The mobility of the young, the elderly, and the disabled, who might otherwise face challenges with traditional transportation methods, could increase (Anderson et al., 2016). CAVs offer newfound independence and easier access to amenities, services, and social opportunities. Cities can optimize the use of space and ensure efficient mobility by considering land use and the urban form of CAVs (Faisal et al., 2019).

The impact on accessibility is likely to vary; rural areas with high street connectivity may benefit, while the impact on urban areas depends on CAV usage (Anderson et al., 2016; Meyer et al., 2017; Soteropoulos et al., 2019). Researchers examined equity issues in lower-income areas of Portland, Oregon. They found that innovative mobility systems can address transportation challenges by enhancing service and reducing costs for public transit, ridesharing, and active transportation (Golub et al. 2019).

The implementation of an autonomous micro-mobility system has the potential to enhance accessibility. These systems effectively address the transportation needs of zones characterized by higher inequity, promoting inclusivity and reducing disparities (Bilal and Giglio, 2023).

2.7 Traffic Control and Operation

The impacts of CAVs on communities are multifaceted and uncertain. Combining the cooperative behavior of CAVs with supportive infrastructure could boost roadway capacity, save travel time, and yield users multiple benefits (Szimba and Hartmann, 2020). By optimizing routes and travel speeds, CAVs can seamlessly navigate through traffic, reducing travel time and leading to smoother and more predictable journeys (Anderson et al., 2016). The dynamic nature of CAVs necessitates dedicated lanes to improve network performance and vehicle throughput (Faisal et al., 2019).

While improved traffic safety is expected, impacts on vehicle miles traveled (VMT) and congestion depend on factors such as CAV adoption rates, SAVs usage, vehicular ownership, driving behavior, and the number of trips (Benkraouda and Chakraborty, 2022). There is significant concern that CAVs might increase car travel, exacerbating congestion and environmental issues (Fraedrich et al., 2019). VMT could increase by 2–47% with full CAV adoption, particularly in wealthier households, potentially increasing energy use, traffic congestion, and air pollution, presenting challenges to environmental and traffic management goals (Taiebat et al., 2019).

The cost associated with travel time and congestion will reduce as commuters can perform certain activities while commuting (Anderson et al., 2016). A simulation study showed potential travel time savings of 27% with Level 5 CAVs and up to 20% with Level 4 CAVs

(Szimba and Hartmann, 2020). In Santander, Spain, Singh et al. (2023) compared performance indicators such as traffic, emissions, and safety and observed that a balanced scenario combining different parking choices performs the best, reducing delays by approximately 32% and decreasing traffic crashes by 67% with 100% CAV market penetration.

SAVs supplementing public transit systems are potentially beneficial to urban development strategies. The technology could redistribute lanes according to peak hours and utilize the saved space for public activities, thereby inviting landscape architects to shape the future of cities with eco-friendly and human-centric public spaces (Yadan, 2019). The impact of SAVs on VMT varies depending on factors such as empty trips, migration effects, ridesharing, road capacity, and vehicle operating and parking costs, with some studies indicating an increase in VMT and others suggesting a potential reduction (Soteropoulos et al., 2019).

2.8 Urban Sprawl and Land Use

CAVs could alter the built environment by affecting densities and suburbanization (Benkraouda and Chakraborty, 2022). CAVs pose a transformative potential for urban life, including the possibility of altering vehicle design, impacting the number of cars, and influencing city residents' living preferences (Duarte and Ratti, 2018). Introducing private CAVs promotes dispersed development patterns, with population growth in distant suburbs and rural regions. At the same time, SAVs can limit urban sprawl or enhance accessibility in rural areas. However, SAVs with reduced travel time and parking requirements contribute to deindustrialization as secondary sector firms relocate from urban areas (Soteropoulos et al., 2019). The introduction of CAVs could require changes in road design, notably the introduction of drop-off areas and reductions in lane widths (Fraedrich et al., 2019).

The advent of CAVs will likely revolutionize urban landscapes, especially regarding parking, freeing up valuable real estate for more efficient uses (Fagnant and Kockelman, 2015). CAVs offer the potential for a significant reduction in required vehicles and parking spaces by replacing private vehicle trips with SAVs, mainly through ridesharing. However, factors such as assumptions on private ownership and model simplifications impact the extent of these reductions (Soteropoulos et al., 2019).

Emerging CAV technology could revolutionize underutilized road systems by transforming up to 80% of existing roads into green infrastructure, enhancing the urban ecosystem's continuity (Yadan, 2019). Land use changes are anticipated, with possible expansions in residential and commercial areas at the expense of agricultural lands (Kang and Kim, 2019). A potential increase in green spaces due to reduced parking requirements is also expected. However, this could alternatively lead to conditions less favorable for pedestrians and cyclists (Bösch et al., 2018; Yadan, 2019; Cohen and Cavoli, 2019; Fraedrich et al., 2019). The transformative potential could contribute to increased sustainability and livability in urban spaces.

2.9 Transportation Demand

The introduction of CAV technologies raises uncertainties regarding their impact on the carsharing market, land use patterns, and the need for tolling policies to manage increased travel demand (Bansal and Kockelman, 2018). A perception-based study showed that areas with poor job accessibility via automobile showed higher interest in CAVs, more anticipated usage, a willingness to pay for the self-driving capability, and reliance on CAVs for long-distance travel (Anderson et al., 2016).

Investments in multimodal transportation are essential to reduce the impact of increased vehicle ownership and promote shared vehicle usage. CAVs and SAVs can work with a multimodal transportation network, particularly public transportation, by providing first-/last-mile connectivity (Gurumurthy et al., 2019; Kolarova et al., 2019). Extensive adoption of private CAVs in the Triangle Region of North Carolina improves network conditions and encourages suburban and rural households to live farther from work (Hasnat et al., 2023).

Promoting high-quality mass transportation, increasing service frequency, and providing complementary services can contribute to increased usage of public transport and improved equity (Booth et al., 2019; Golub et al., 2019). However, SAV was perceived as less attractive than privately owned CAVs, highlighting a potential conflict between individual benefits and societal goals, leading to important policy considerations (Kolarova et al., 2019). A study in Austin, Texas, showed that implementing road pricing during peak periods reduces VMT and increases SAV demand, resulting in higher revenue for fleet managers (Gurumurthy et al., 2019). SAVs can generate approximately $100 per vehicle per day, but only at low-fare levels (Gurumurthy et al., 2019).

Rapid technological advancements and the rise of autonomous driving pose significant implications for policy and transport planning. Kolarova et al. (2019) revealed a 41% reduction in the value of travel time savings for commuting trips with autonomous driving. At the same time, no significant changes were found for leisure or shopping trips. In contrast, a high market share of CAVs leads to deteriorated network performance and increased urban households (Hasnat et al., 2023).

2.10 Long-Range Transportation Plans

The success of the transition toward CAVs depends on the acceptance and preparedness of stakeholders, particularly local authorities and urban transportation planners (Gyergyay et al., 2019). CAVs can contribute to long-term effects such as dispersed urban development, reduced parking demand, and improved energy efficiency (Rahman and Thill, 2023). Previous research proposed a reconsideration of strategic stances on CAV research and development, given the disparity between urban transport planning objectives and the focus of federal government policies (Fraedrich et al., 2019). While CAVs could enhance mobility and accessibility for non-drivers like the elderly and the disabled, CAVs could negatively impact active transportation, social equity, and the environment (Benkraouda and Chakraborty, 2022). According to a study, the actions of planning organizations heavily influence the impacts of CAVs with potential levers ranging from traffic control strategies to infrastructural changes and design guidelines (Benkraouda and Chakraborty, 2022). Scenario planning can offer direction for planners to understand the future impacts and align planning objectives with the desired outcomes of increased mobility, accessibility, and time-travel reliability (Benkraouda and Chakraborty, 2022).

2.11 Laws and Policies

Government interventions can be divided into five categories: planning/land use, regulation/policy, infrastructure/technology, service provision, and economic instruments. Each category contains interventions applicable at city, regional, or state levels to manage congestion and protect accessibility (Cohen and Cavoli, 2019).

Beyond technological advancements and consumer preferences, others, such as governmental regulations and incentives, private sector investment, and business logistics in the freight sector can also influence the growth and deployment of CAVs (Benkraouda and Chakraborty, 2022). Policies and funding provisions from the state can advance deployment while resolving liability concerns and defining a legal framework for CAVs can foster more trust and further adoption (Fagnant and Kockelman, 2015; Taeihagh and Lim, 2019).

The parking scene is expected to undergo significant changes with the rise of CAVs. Reassessing and studying parking regulations, including building codes, pricing, and policies, is recommended (Cohen and Cavoli, 2019). Strategies such as reducing parking stock, reclaiming on-street and off-street parking facilities in dense areas, and introducing more drop-off/pick-up locations, especially at transportation hubs, are suggested (Cohen and Cavoli, 2019; Faisal et al., 2019). Combining charged-parking policies with additional regulations can address potential social equity issues and improve mobility through accessibility to SAVs (Zhang and Guhathakurta, 2017). Policies should prioritize and subsidize shared/collective CAVs, enhance public transportation services, improve cycling and pedestrian networks, and ensure seamless integration between automated vehicles and other modes of transportation (Booth et al., 2019; Cohen and Cavoli, 2019).

Federal and state regulations, private sector investments, and transparent legal CAV frameworks influence CAV acceptance and growth (Fagnant and Kockelman, 2015; Taeihagh and Lim, 2019). Despite current uncertainties regarding the types of early adopters and the adoption rate, efforts are being made to spread awareness about CAVs and keep the public informed.

The role of private sector investment in research and development must be considered, as it could significantly accelerate CAV proliferation rates (Benkraouda and Chakraborty, 2022). A study suggests overcoming barriers to mass adoption of CAVs, such as high costs, inconsistent licensing standards, unresolved liability, security concerns, and potential privacy breaches, through expanded federal research and the creation of a national licensing framework, setting appropriate standards for liability, security, and data privacy (Fagnant and Kockelman, 2015).

2.12 Research Questions

The literature review highlights that CAVs will impact traffic operations, mobility, accessibility, equity, safety, parking, land-use, urban sprawl, and the economy. State and federal agencies must identify the trajectory of CAVs development, anticipate the impact of CAVs in their jurisdiction, identify the specific data requirement for CAVs, and formulate policies and regulations to accommodate the anticipated impacts. This study focuses on the following research questions.

(a) How do the data requirements for CAVs vary compared to traditional vehicles?
(b) What should stakeholders do to accommodate the impact of CAVs and ensure a CAV-inclusive transportation system?

3. Research Methodology

Effective large-scale planning for accommodating CAVs remains a challenge because of (a) the novelty of the technology, (b) uncertainties associated with the pace of technological change and adoption of CAVs, and (c) the uncertain impact of CAVs on travel demand, safety, roadway design, employment, and urban form. Moreover, the uncertainties could vary by the type of travel (passenger or freight), functional class (highway or urban roads), and socioeconomic context. Due to these uncertainties, regulations and policies promoting desirable outcomes remain undefined or unclear. The communities must anticipate the trajectories of changes CAVs could affect and develop plans to accommodate these impacts.

This study adopts a systematic research methodology to identify (a) the impact of CAVs and (b) data requirements for CAVs to accommodate their impacts and foster a CAV-inclusive environment. The research methodology consists of the following steps:

3.1 Reviewing Existing Literature

A comprehensive review of existing literature was conducted. The impact of CAVs on mobility, traffic operations, safety, urban sprawl, land-use parking, and the economy was identified and documented. Moreover, recommended policy-level and infrastructure-level changes to accommodate the varying impact of CAVs were also documented.

3.2 Conducting Focus Group Discussions

In this step, focus group discussions were conducted to elicit the perception of twenty professionals in North Carolina towards varying nuances of CAVs. This step explored data requirements, privacy and security, and the potential impacts on transportation, land use, safety, and security.

3.3 Capturing Perceptions Of Practitioners And Industry Experts

This step captured the perception of practitioners and industry experts related to the impact of CAVs, and potential policy-level and infrastructure-level recommendations for accommodating the impact of CAVs. The perceptions of eighteen practitioners and four industry experts were captured and analyzed. The results of this step helped in understanding (a) how practitioners and industry experts perceive the impact of CAVs and (b) how CAV data requirements essentially vary from traditional vehicles.

3.4 Proposing Data Readiness Framework

Based on the results of steps two and three, a data readiness framework is proposed. The proposed data readiness framework sets priorities for stakeholders, such as the NCDOT, in formulating policies and upgrading infrastructure for a CAV-inclusive transportation environment.

4. Focus Group Discussions

CAVs are the subject of much discussion—in professional circles and among the public. Management and regulatory regimes remain uneven and often in limbo, even as technology rapidly changes and evolves. This uncertainty plays out in both professional settings and in public attitudes, as the potential benefits (e.g., safety, mobility, and efficiency) and risks (e.g., equity and access, privacy, and changing land use) are weighted and debated.

Like other transportation agencies, NCDOT collects and manages voluminous data to track crashes, understand the characteristics of roads and drivers, manage law enforcement activity, and more. With the arrival of CAVs certain to disrupt the established suite of tools and practices used to collect data from various sources, it is time to prepare for changing data collection, management, and safeguarding needs. The data to be collected will be different and more extensive than for conventional vehicles and will affect policy and planning for transportation, land use, built environment, safety and security, and more.

4.1 Purpose and Scope

The motivating question for this project is: How do data requirements for CAVs and other new technologies differ from those of prevailing transportation systems? *Emerging Issues and Data* is one of nine areas of emphasis in the North Carolina Strategic Highway Safety Plan (http://ncshsp.org). The main goal is to improve data and data systems in the state and to address safety concerns. Five strategies include: (1) improve crash data quality, (2) improve accuracy and completeness of roadway inventory data, (3) improve data, (4) increase the usefulness of existing traffic safety data, and (5) accommodate new emerging highway safety concerns. These five strategies all are relevant to this project.

This task performed by the Appalachian State University team focused specifically on exploring how transportation professionals across North Carolina, in a variety of geographic and professional settings, view the arrival of CAVs in their regions and on their streets, what they see as the potential benefits and pitfalls of this transition, and what expectations they have for data privacy and security and public concerns relating to data. This task focused primarily on the exploratory study using qualitative data collected from transportation experts, whose opinions and attitudes are more likely to be shaped in part by knowledge of and familiarity with the ongoing debates about CAV technology, management, and policy. Another component of this task involved an online survey of young adults, assessing their interest and comfort with using, sharing, and owning CAVs. Although surveying the general public to assess perceived safety and comfort with CAVs and their data requirements was pushed beyond this project's scope by personnel changes early in the project, the completed (and published) survey of young adults provides useful findings that will support further study.

4.2 Research Approach

This task used key informant interviews in the format of focus groups to elicit the perceptions, opinions, and insights of 20 North Carolina transportation professionals working across the state, mountains to the sea, and in a variety of professional roles. The qualitative data generated by the interviews were subjected to content analysis to identify major themes and represent the nuanced views of these professionals. An online survey of young drivers (n=463) generated statistically significant results regarding attitudes toward using, sharing, and owning CAVs.

4.3 Literature Review

Nationwide, states have taken a variety of pathways to prepare for CAVs and their associated data needs, including data management plans tied to active CAV testing, “roadmaps” in anticipation of future needs, and more passive “wait and see” stances. This state specific variation in planning for CAVs extends to differences in associated concerns, such as insurance requirements, identifying vehicles as CAVs, standby driver requirements, and more.

A large body of methodological guidance for qualitative methods includes several texts useful for data collection using surveys and focus groups (Stewart et al., 2007; Merriam, 2009; Dillman, 2014; Besen-Cassino and Cassino, 2018).

The broader literature on CAVs touches on technology and engineering, management and regulation, liability and insurance, cost and equity considerations, mobility and accessibility, impacts on land use and travel behavior, and much more. Within that literature is a body of work related to attitudes and perceptions—among the general public and professionals in the transportation sector. Recent work has considered perceptions about the technology (Bansal and Kockelman, 2016; Liu et al., 2018) and willingness to adopt (Cepolina and Farina, 2013; Bansal and Kockelman, 2016; Panagiotopoulos and Dimitrakopoulos, 2018; Talebian and Mishra, 2018; Asgari and Jin, 2019; Gkartzonikas and Gkritza, 2019; Hardman et al., 2019; Spurlock et al., 2019), as well as how attitudes relate to factors such as age, education, gender, income, or parenthood (Dias et al., 2017; Charness et al., 2018; Lee and Mirman, 2018; Pakusch et al., 2018a; Berliner et al., 2019) and perceived risk (Brell et al., 2018; Liu et al., 2018, 2019; Raue et al., 2019). The importance of public acceptance of CAVs is discussed by Liu et al. (2019), Panagiotopoulos and Dimitrakopoulos (2018), and Raue et al. (2019), among others.

A dominant narrative in recent years is associated with the ‘3 revolutions’ of the CAV transition—electrified, connected, and shared (through car- or ridesharing, ride-hailing, or mobility-as-a-service models). The assumption of shared mobility as a key pillar of the CAV transition (Cohen and Kietzmann, 2014; Fulton et al., 2017) is widespread but not ubiquitous and is the subject of much debate (Krueger et al., 2016; Currie, 2018; Hubbard, 2018; Nazari et al., 2018; Pakusch et al., 2018a; Merfeld et al., 2019; Pettigrew et al., 2019; Spurlock et al., 2019; Watkins, 2018; Whittle et al., 2019).

Safety is arguably the most frequently and forcefully promoted benefit of CAVs, with the potential to reduce the number and severity of crashes. The literature on perceived vs. measured safety is mixed and reflects the complex changing interaction of technology, familiarity, habits, and trust (Brell et al., 2018; Liu et al., 2019).

Mobility based on shared modes is another prime argument for CAVs in society, particularly for its potential to address the needs of underserved populations such as non-driving youth, seniors, and disabled travelers, as well as low-income and other mobility-limited groups (Dias et al., 2017; Charness et al., 2018; Lee and Mirman 2018). Ride-hailing, ride-sharing, and other on-demand services have been growing steadily among other groups as well, attracted to the convenience, cost savings, and liberated time that shared mobility offers in urban environments where vehicles are expensive to maintain and store (Barth and Shaheen, 2002;

Cohen and Kietzmann, 2014; Alessandrini et al., 2015; Fulton et al., 2017; Dowling et al. 2018). The pathway by which automated, electrified, and shared vehicles will unfold is uncertain and will raise new questions about street design, liability, and policies to protect travelers of all modes (Cohen and Kietzmann, 2014; Fagnant and Kockelman, 2015; Asgari et al., 2018; Campbell, 2018; Metz, 2018).

Privacy and personal safety are emerging as a lagging focus of concern as individuals hear, read about, and increasingly observe CAVs in the environment. Because the CAV transition is premised partly on the ubiquitous use of information technology to hail and track vehicles, mobility providers and regulators will increasingly be called upon to address privacy and security concerns (Jin et al., 2018). Another area of concern is the likely displacement of transportation workers such as transit and truck drivers (Cepolina and Farina, 2014; Currie, 2018; Fulton et al., 2018; Pakusch et al., 2018b) although some of this may be offset by new jobs created by the CAV transition.

4.4 Task Objectives and Data Types

The primary objective of this task is to complement the project (identifying CAV data needs relating to vehicles, infrastructure, and crashes) by assessing the level of knowledge, interest, and concern about CAVs and data on the part of North Carolina transportation professionals and surveying the public about their level of comfort with CAVs.

The data from key informant interviews are qualitative and exploratory, collected through interviews with subject matter experts ("key informants") using a semi-structured interview instrument, which provides structure from repeated questions while allowing freeform discussion and the pursuit of unanticipated or novel themes. Because the focus of this research is emerging and evolving, and because of their various professional specializations, key informants have varying levels of knowledge. Although the project was conceived to focus narrowly on CAV data needs, preliminary analysis revealed that transportation professionals have a high level of interest but a relatively low level of specific knowledge in data privacy and security. Therefore, an early draft interview instrument was revised to add more general questions about expectations for the arrival of CAVs and their penetration into the travel environment.

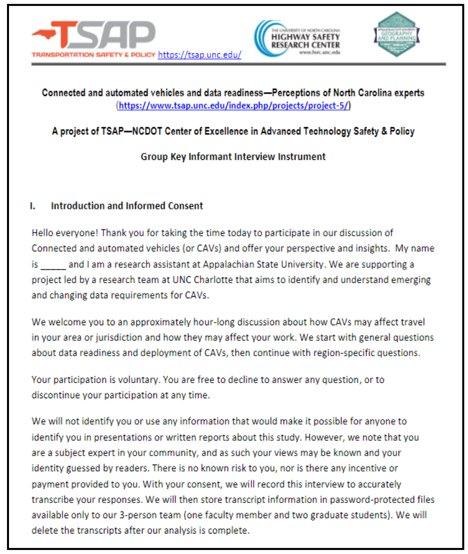
The survey collected attitudinal data as ordinal responses using 4-point Likert-scale questions and other data (ratio and nominal data) for sociodemographic and other measures; statistical analysis was conducted in Stata.

4.5 Methods, Results, and Findings

This task used established methods for qualitative data collection to understand and report the perceptions and insights of North Carolina transportation professionals relating to CAVs and data concerns. Interviews probed key informants for their views on (1) CAV data—what should be collected—and by whom, as well as protocols and responsibility for storage, (2) likely public concerns about privacy and security, and (3) anticipated impacts of CAVs in their regions and on their professional work. A separate component of this project surveyed young people about their level of comfort using, sharing, and owning CAVs.

4.5.1 Key Informant Interviews

Researchers interviewed key informants (transportation experts) representing North Carolina municipalities, counties, metropolitan planning organizations (MPOs), rural planning organizations (RPOs), and NCDOT in small focus groups (group interviews) of two to three participants. Researchers identified the key informants through a systematic review of public agencies with a transportation function, using publicly available contact information, and with an effort to reach professionals across the state (mountain, piedmont, and coastal communities) and from communities ranging from small towns to large cities. Researchers recruited key informants with a standard email used in all communications, which included the purpose of the study, IRB status (exempt, HS-23-119), and contact information for the research team.


TSAP TRANSPORTATION SAFETY & POLICY https://tsap.unc.edu/ THE UNIVERSITY OF NORTH CAROLINA HIGHWAY SAFETY RESEARCH CENTER www.hsrc.unc.edu GEOGRAPHY AND PLANNING

Connected and automated vehicles and data readiness—Perceptions of North Carolina experts
(https://www.tsap.unc.edu/index.php/projects/project-5/)

A project of TSAP—NCDOT Center of Excellence in Advanced Technology Safety & Policy

Group Key Informant Interview Instrument

I. Introduction and Informed Consent

Hello everyone! Thank you for taking the time today to participate in our discussion of Connected and automated vehicles (or CAVs) and offer your perspective and insights. My name is _____ and I am a research assistant at Appalachian State University. We are supporting a project led by a research team at UNC Charlotte that aims to identify and understand emerging and changing data requirements for CAVs.

We welcome you to an approximately hour-long discussion about how CAVs may affect travel in your area or jurisdiction and how they may affect your work. We start with general questions about data readiness and deployment of CAVs, then continue with region-specific questions.

Your participation is voluntary. You are free to decline to answer any question, or to discontinue your participation at any time.

We will not identify you or use any information that would make it possible for anyone to identify you in presentations or written reports about this study. However, we note that you are a subject expert in your community, and as such your views may be known and your identity guessed by readers. There is no known risk to you, nor is there any incentive or payment provided to you. With your consent, we will record this interview to accurately transcribe your responses. We will then store transcript information in password-protected files available only to our 3-person team (one faculty member and two graduate students). We will delete the transcripts after our analysis is complete.

Figure 1 First page of interview instrument

4.5.2 Data

Interviewers used a semi-structured interview instrument that contained questions relating to the key concerns (CAV data privacy and security concerns and CAV impacts on communities and the transportation profession). Two researchers conducted interviews over Zoom, recorded (with permission of participants), and transcribed with a voice-to-text tool (Otter.ai). The researchers cleaned the resulting transcripts by closely reading, correcting clear errors, and noting major and minor themes that emerged. They turned the themes into a structure of codes and code groups that they loaded onto the content analysis software Atlas.ti (version 23, atlasti.com), along with the transcripts. Two researchers coded each transcript using an inductive/deductive strategy where initial codes and code groups are revised with free coding during the process. The coding process produced 526 words or passages in nine transcripts assigned one or more of 77 different codes. The researchers used Atlas.ti tools to produce a word cloud (counting word frequencies in the raw text data) and code frequencies and co-occurrences (counting codes attached to text data by the research team and showing relationships among them), which supported analysis and discussion of the data.

4.6 Survey—Young People and CAVs

This component of the study used an online survey to test the assumption that young adults are eager to adopt CAVs and, importantly for the ‘3 revolutions’ model, to do so through shared mobility rather than owning personal vehicles. The survey asked three questions:

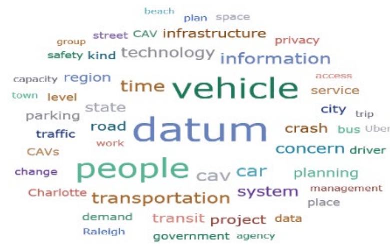


Figure 2 Most frequent words

1) How comfortable would you feel riding in a driverless car in mixed traffic (i.e., with other driverless vehicles, human-operated vehicles, pedestrians and bicyclists, buses, etc.) for everyday travel?
2) How comfortable would you feel relying on shared or hailed driverless vehicles instead of owning/renting a personal motor vehicle?
3) Would you like to own a driverless vehicle?

4.7 Findings, Conclusions, and Recommendations

The survey, completed in 2021, provides findings that suggest useful future research. The findings are summarized in this section.

4.7.1 Key Informant Interviews

The data from key informant interviews suggest that North Carolina transportation professionals are interested in the CAV discussion and engaged in active discussions about what tools, technology, and regulations will be needed—but they are largely uncertain about the details of what and when actions need to be taken. The exception to this is the small number of key informants who have first-hand expertise in CAVs. Transportation professionals in the focus groups were thoughtful, knowledgeable, and committed to continuing to learn about and apply emerging information and guidance about CAVs, and to communicate with the public about approaching changes and possible impacts. At the same time, many expressed a sense of disorientation—not knowing where to turn for reliable and authoritative information. Other sentiments were concern about data requirements, the burden on public agencies, and the risk to individual travelers and their privacy and personal security.

The results suggest the need for clearer technical guidance for transportation professionals on how to prepare for CAVs in state, regional, and local agencies, as well as materials to support community engagement in the discussion of current and future CAV development, given high-interest and concern on the part of the public. Concerns expressed about high data requirements, threats to personal safety and security posted by extensive data collection by private parties, and the need for regulatory and policy development all point to the need for proactive efforts by transportation authorities.

4.7.2 Young People and CAVs

The survey of young adults and their level of comfort with using, sharing, and owning CAVs was designed as a first attempt at assessing public attitudes and intended to test the assumption that is woven into much current discussion that extensive use of shared mobility is key to the CAV transition. With 510 responses, the analysis focused on 463 completed responses from adults aged 18-44. The major finding that emerged from the analysis was relative ambivalence toward CAVs (using, sharing, or owning), with responses heavily concentrated in the middle two categories of the 4-point Likert scale ("somewhat comfortable" and "somewhat uncomfortable") and fewer responses in the "very" extremes. Cross-tabulations broke down the responses by age, gender, and urban city, revealing small but statistically significant differences, of which the most notable is the more positive attitudes toward CAVs among males. The findings suggest that the assumption of high interest in using and sharing CAVs may not be clear-cut.

Additional study is warranted to understand better how travelers form their perceptions and attitudes about CAVs and the implications for continued CAV development and planning.

5. Practitioners and Industry Expert Survey

Researchers designed a well-structured questionnaire to capture the understanding of what these knowledgeable individuals perceive and suggest about CAVs, particularly regarding the necessary policy-level and infrastructure-level changes needed to accommodate CAVs. It is essential to mention that employees of the state and regional departments of transportation (DOTs), private consultants, and consulting firms were considered practitioners. In contrast, people involved in manufacturing CAVs and related parts were considered industry experts. After receiving IRB approval, researchers initiated the survey in October 2022 and kept the survey open for seven months, garnering 22 responses. The respondents to this survey represent a broad spectrum of organizations, including state, city, or regional transportation departments, as well as consultants and industry experts. Furthermore, their professional roles within these organizations vary, encompassing fields such as transportation planning, road design, traffic signals or Intelligent Transportation Systems (ITS), traffic safety, road design, and pavement.

This chapter presents the results from the analysis of the responses from the survey. The chapter is divided into three sub-chapters: Time horizon, anticipated impact, and anticipated infrastructural/policy change to accommodate the impact.

5.1 Time Horizon

A part of the survey consists of questions that provide a basic idea about when fully automated vehicles will be available to commuters and when the necessary infrastructural and policy changes should be implemented.

5.1.1 Expected Time When Fully Automated Vehicles Will Be Available to Commuters

The big question amongst researchers these days is when fully automated vehicles will be available to commuters. The availability of CAVs will govern the adoption rate and priority for implementing different policies for a CAV-inclusive traffic environment. Figure 3 shows the responses of practitioners and industry experts regarding their anticipated time when fully automated vehicles will be available to commuters.

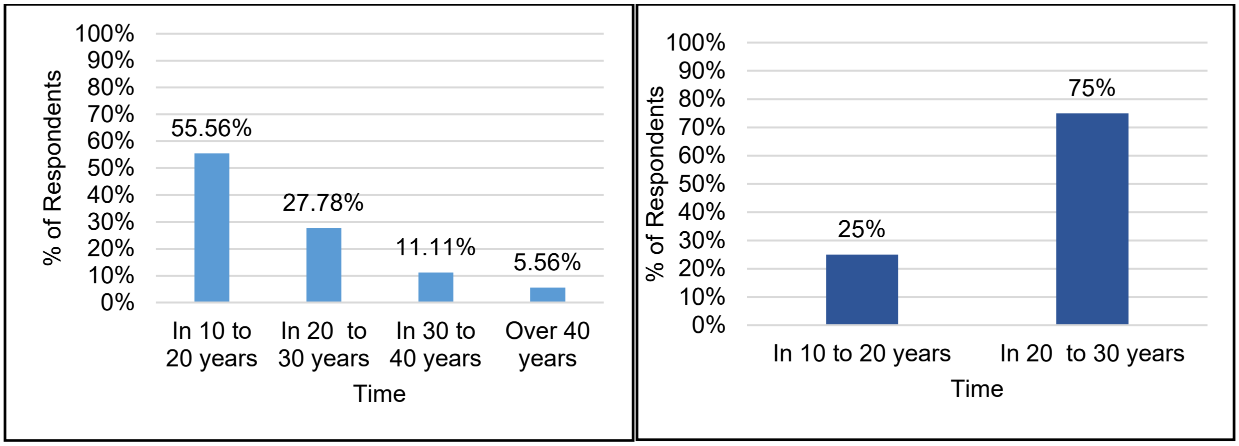


Figure 3 Expected time when fully automated vehicles will be available to the commuters: (left) respondents are practitioners and (right) respondents are industry experts.

About 56% of practitioners who responded to the survey think that fully automated vehicles will be available in the next 10 to 20 years, while 75% of industry experts who responded to the survey think that they will be available in the next 20 to 30 years. According to Litman (2023), SAVs, self-driving taxis, and ride-hailing are expected to be available during the 2030s and 2040s.

5.1.2 Expected Time When Infrastructure Will Be Ready for Fully Automated Vehicles

The infrastructure needs to be ready to communicate when CAVs are available to commuters. Responders were asked about infrastructure readiness, and the results are summarized in Table 1.

Table 1 Expected time when the infrastructure will be ready for CAVs

Option	% of Practitioners	% of Industry Experts
Ready Now	9.09	0
In 1 to 5 years	18.18	25
In 5 to 10 years	22.73	25
In 10 to 20 years	31.82	0
In 20 to 30 years	13.64	50
Over 30 years	4.55	0

Most practitioners who responded to the survey think that the infrastructure in their state/region/city/town will be ready for the CAVs in 10 to 20 years. However, industry experts believe the infrastructure will be ready in 20 to 30 years. Few practitioners and industry experts believe that infrastructure is ready now for CAVs.

5.1.3 Expected Time When Policy and Regulations Regarding CAVs Will Be Implemented

As the operation of CAVs will be different from normal vehicles, federal and state governments need to make amendments to different policies and regulations to foster a CAV-inclusive environment. Table 2 summarizes the perceptions of practitioners and industry experts regarding when the policies and regulations regarding CAVs will be implemented in the United States.

Table 2 Expected time when policies and regulations regarding CAVs will be implemented in the United States

Option	% of Practitioners	% of Industry Experts
In 0 to 5 years	16.67	-
In 5 to 10 years	38.89	50
In 10 to 20 years	27.78	50
In 20 to 30 years	11.11	-
Over 30 years	5.56	-

About 39% of practitioners and 50% of industry experts who responded to the survey think that the policies and regulations regarding CAVs will be implemented in the United States in 5 to 10 years. However, few think these policies and regulations will be implemented in 10 to 20 years. Overall, one can expect these implementations in 5 to 20 years.

These time horizons are essential in understanding when different policies should be implemented, i.e., it enables defining the priority of implementing different policies. Based on the results above, this study classified priority into three levels (a) high-priority (less than 10 years), moderate-priority (between 10 to 20 years), and (c) low-priority (greater than 20 years).

5.2 Anticipated Impacts

CAVs have huge operational, economic, and political impacts. The anticipated impacts from the perspective of practitioners and industrial experts are summarized next.

5.2.1 Crash/Safety

The effect of CAVs on safety has been a discussion for a few years. CAVs will penetrate the market gradually over time. Moreover, levels of automation make this transition difficult to predict. Past researchers studied the effect of CAVs on safety with different penetration rates. Fitch et al. (2014) investigated the effectiveness of using multiple driver assistance warning systems in multiple near-crash scenarios with forward collision warning (FCW) and lane departure warning (LDW); multiple warning systems yielded better results. Genders and Razavi (2016) revealed that market penetration of CAVs under 40% contributes to safety, and beyond 40% reduces safety. Moreover, CAVs reduce the number of traffic conflicts by 20% to 65%, with penetration rates between 50% and 100% (Morando et al., 2018).

About 67% of practitioners and 100% of industry experts who responded to the survey think CAVs will reduce traffic injuries and fatalities. Figure 4 shows the anticipated percent reduction in traffic injuries and fatalities by practitioners and industry experts who responded to the survey. From Figure 4, about 37% of practitioners who responded to the survey perceive that traffic injuries and fatalities will be reduced by 40% to 60%, and 50% of industry experts who responded to the survey perceive that traffic injuries and fatalities will be reduced by 80% to 100%. The perceptions of practitioners and industry experts align with the results reported in the literature.

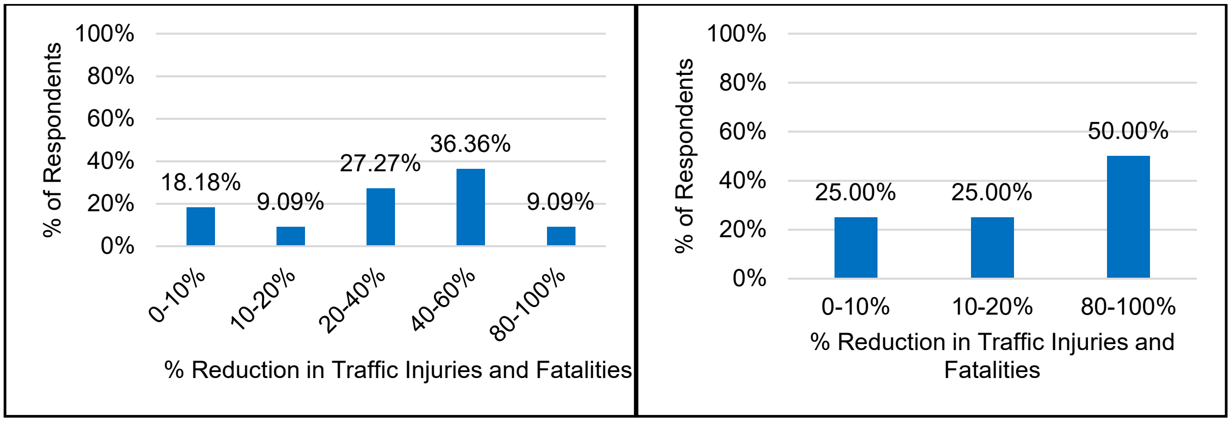


Figure 4 % of reduction in traffic injuries and fatalities: (left) respondents are practitioners and (right) respondents are industry experts.

5.2.2 Operations

CAVs are expected to impact travel times, delays, congestion, and VMT. The percentage of reduction in the travel time anticipated by practitioners and industry experts is shown in Figure 5.

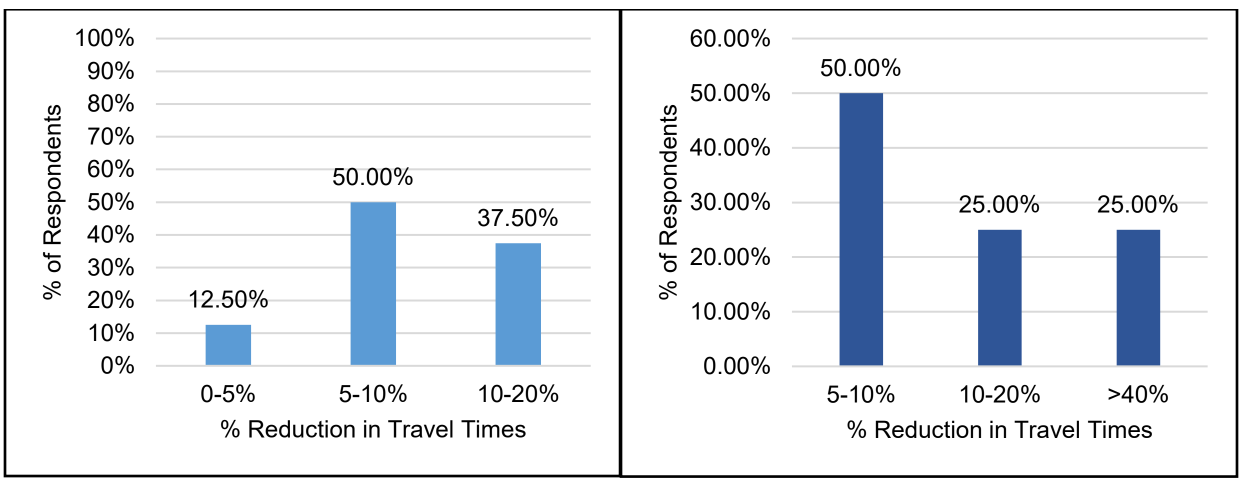


Figure 5 Anticipated % of reduction in travel time: (left) respondents are practitioners and (right) respondents are industry experts.

About 50% of practitioners and industrial experts who responded to the survey think CAVs will reduce travel times by 5% to 10%. However, 25% of industry experts who responded to the survey perceive a greater than 40% reduction in travel times.

About 56% of practitioners and 50% of industrial experts who responded to the survey think CAVs will reduce the VMT. However, about 28% of practitioners and 50% of industrial experts who responded to the survey were unsure if CAVs will reduce the VMT. Clements and Kockelman (2017) noticed an increase in VMT. The increased VMT may come up with an increase in congestion. However, automated vehicles improve road capacity more than connected vehicles (Talebpour and Mahmassani, 2016). Cooperative adaptive cruise control (CACC) will likely improve traffic flow; adaptive cruise control (ACC) can cause bigger traffic jams than human drivers (Milanes and Shladover, 2014). About 28% of practitioners and 75% of industrial experts who responded to the survey think CAVs will reduce traffic jams. However, about 44% of practitioners and 25% of industrial experts who responded to the survey were unsure if CAVs would reduce traffic congestion.

5.2.3 Mobility of Elderly and Disable People

About 78% of practitioners and 100% of industry experts who responded to the survey agree that if CAVs become widespread, children, the elderly, and disabled people can travel more independently. However, about 22% of the practitioners who responded to the survey think it depends on the price point and affordability.

5.2.4 Economic Impact on Main Market Sectors

Besides the safety and operational impacts, CAVs are supposed to have a substantial economic impact on various industry sectors. This impact can be positive or negative depending on the type of industry. As practitioners and industry experts better understand the existing market trends and are supposed to be updated with the ongoing research, they can give an idea about the direction of impact on various industry sectors. Tables 3 and 4 summarize the perception of practitioners and industry experts on different types of impact on different sectors.

Table 3 Perception of practitioners on the impact on different sectors

Sector	Positive	Negative	No impact	Not sure
Auto repair and maintenance	33.33	27.78	11.11	22.22
Automotive industry	61.11	16.67	5.56	11.11
Construction of roads and motorways	27.78	27.78	5.56	33.33
Electrification/energy	38.89	38.89	5.56	11.11
Freight	72.22	5.56	5.56	11.11
Insurance	27.78	44.44	5.56	16.67
Land development	22.22	22.22	22.22	27.78
Law enforcement/police	50	16.67	11.11	16.67
Medical services	38.89	16.67	16.67	22.22
Oil and gas	33.33	27.78	5.56	27.78
Public health	55.56	5.56	-	27.78
Taxi services	22.22	38.89	11.11	22.22
Technology (electronics and software)	77.78	-	-	16.67
Transportation	72.22	11.11	-	11.11
Telecommunication	44.44	11.11	16.67	22.22
Vehicle registration	22.22	16.67	33.33	22.22

Table 4 Perception of industry experts on the impact on different sectors

Sector	Positive	Negative	No impact	Not sure
Auto repair and maintenance	75	-	25	-
Automotive industry	75	-	-	25
Construction of roads and motorways	75	-	-	25
Electrification/energy	100	-	-	-
Freight	100	-	-	-
Insurance	25	25	-	50
Land development	75	-	25	-

Law enforcement/police	50	25	-	25
Medical services	75	-	-	25
Oil and gas	50	50	-	-
Public health	100	-	-	-
Taxi services	50	25	-	25
Technology (electronics and software)	100	-	-	-
Transportation	75	-	-	25
Telecommunication	100	-	-	-
Vehicle registration	25	25	25	25

As the CAVs are supposed to operate on electric energy, the annual energy consumption of private vehicles is expected to decrease by 15% (Taiebat et al., 2019). Responses from practitioners and industry experts are fairly similar. Most practitioners and industry experts who responded to the survey think that CAVs will have a positive economic impact on all industry sectors. Practitioners and industry experts expect a positive impact of CAV on the automotive, freight, technology, law and enforcement, and telecommunication sectors. Most respondents are unsure about the effect of fully automated vehicles on the insurance sector; however, a few think it will have a negative impact. Moreover, the impact of CAVs on the oil and gas sector is uncertain.

The transportation industry will certainly benefit from the widespread use of CAVs. However, people working in transportation-related industries (such as rental car agencies, taxis, transit system operators, rideshare services, delivery agents, etc.) may lose their jobs. About 39% of practitioners and 50% of industry experts who responded to the survey think that people in transportation-related industries will lose their job. On the other hand, about 44% of practitioners and 50% of industry experts who responded to the survey think these people will not lose their jobs.

5.2.5 Preference for Shared Mobility

The widespread use of the CAVs may happen sooner or later. Analyzing whether people prefer shared-mobility options over owning a private CAV is also necessary. Figure 6 shows the percentage of people that the respondents think will prefer shared-mobility options over owning a private CAV.

About 28% of practitioners and 75% of industry experts who responded to the survey think people prefer shared mobility options over owning a private CAV. About 50% of practitioners who responded to the survey are still unsure.

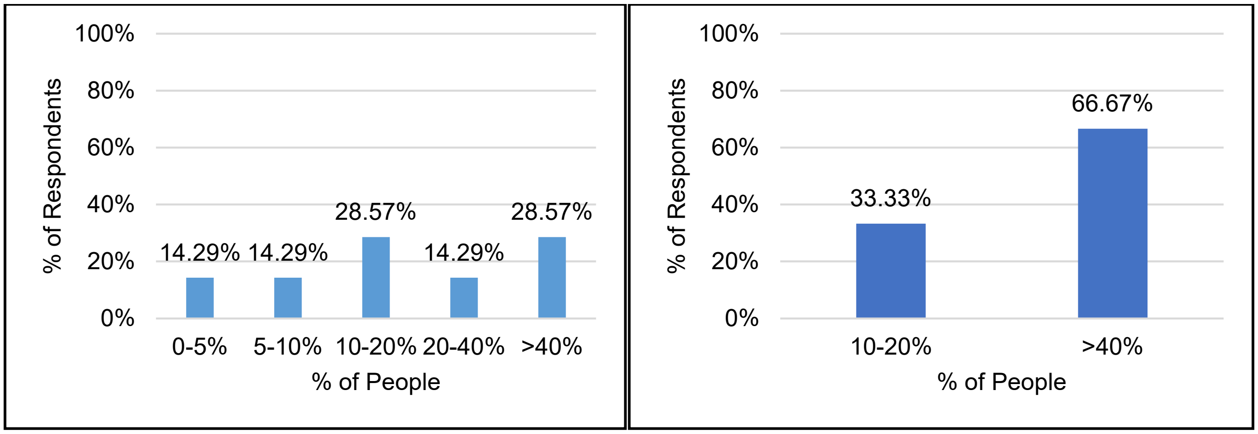


Figure 6 % of people that the responders think will prefer shared-mobility options than owning a private CAV: (left) respondents are practitioners and (right) respondents are industry experts.

Since automation can significantly reduce the operating costs for taxi and ride-hailing fleet owners or managers, transportation network companies (like Lyft, Uber, and Didi) are running CAV tests by investing considerable resources (Buhr, 2017) and developing strategic collaborations with automakers and governments (Russell, 2017) for future, large-scale SAV deployments. Auto manufacturers like Ford, GM, Fiat Chrysler, BMW, Daimler, and Volvo are also considering the possibility of serving as SAV providers (Stocker and Shaheen, 2017). In the case of all-electric SAVs, charging infrastructure investments and battery size/vehicle range can be crucial to the fleet's competitive performance (Loeb et al., 2018). In 2019, it was estimated that the worldwide sale of CAVs would hit 28.5 million units, and shared vehicles are expected to account for 18% of global passenger mileage (Wagner, 2019). These changes suggest that CAVs will have a significant economic impact on the different sectors worldwide, and the survey results support this notion.

5.2.6 Other Planning Aspects

Planners and decision-makers need more clarity on the expected changes due to the large adoption of CAVs in terms of trip length, parking demand, effect on transit ridership, and urban sprawl. In a study by Hörl (2016), introducing SAVs led to increased VMT, and SAVs attracted public transportation users rather than private car owners. Liu et al. (2017) indicated that SAVs are preferable for short-distance trips compared to public transit for travelers without private vehicles. Moreover, cooperation and coordination among CAVs can help resolve the inefficiencies with drop-off, pick-up, and parking (Loke and Aliedani, 2018). Further, CAVs could eliminate parking-related problems, especially in dense areas, and significantly decrease parking costs (Tian et al., 2019; Millard-Ball, 2019). CAVs will have detrimental impacts on land use and sprawl by straining transportation demand and infrastructure capacity (Szimba and Hartmann, 2020). Tables 5 and 6 summarize the perceptions of practitioners and industry experts to the questions related to the topics mentioned above.

Table 5 Anticipated effect of CAVs by practitioners on various planning aspects

Do you think…	Yes (% response)	No (% response)	Remains the same (% response)	Not sure (% response)
CAVs are more appropriate for shorter rides?	22.22	33.33	-	44.44
CAVs till reduce parking demand?	44.44	11.11	11.11	27.78
CAVs will reduce transit ridership?	11.11	50	38.89	-
Widespread adoption of CAVs will lead to urban sprawl?	33.33	33.33	-	33.33

Table 6 Anticipated effect of CAVs by industry experts on various planning aspects

Do you think…	Yes (% response)	No (% response)	Not sure (% response)
CAVs are more appropriate for shorter rides?	50	25	25
CAVs till reduce parking demand?	50	25	25
CAVs will reduce transit ridership?	25	75	-
Widespread adoption of CAVs will lead to urban sprawl?	50	25	25

Inconsistent results can be noted between the perception of practitioners and industry experts. Most of the practitioners refuse or are not sure whether CAVs would be more appropriate for shorter rides. On the other hand, 50% of industry experts who responded to the survey think CAVs are more appropriate for shorter rides. Most practitioners and industry experts who responded to the survey think that CAVs will reduce parking demand, and very few think that they will not reduce the parking demand or that there will barely be any change. Most practitioners and industry experts who responded to the survey think CAVs will not reduce transit ridership. Very few think that CAVs will reduce transit ridership. At the same time, they have a neutral response to the urban sprawl caused by the widespread adoption of CAVs.

The use of CAVs can differ by road functional class, as traffic conditions vary across the road functional class. Table 7 shows that the respondents replied negatively to the restriction of CAVs on the respective road functional class. Most practitioners and industry experts who responded to the survey think CAVs should not be restricted to functional classes. However, 75% of industry experts who responded to the survey think CAVs should be restricted to local roads.

Table 7 Restricted use of CAVs on the road functional class

Road functional class	% of Practitioners		% of Industry Experts	
	Yes	No	Yes	No
Urban interstates/freeways	22.22	66.67	0	100
Urban arterials	22.22	72.22	0	100
Urban collectors	11.11	77.78	0	100
Urban local roads	11.11	83.33	75	75
Rural interstates/freeways	27.78	66.67	0	100
Rural highways	22.22	66.67	25	75
Rural local roads	11.11	72.22	25	75

5.3 Anticipated Infrastructural / Policy Changes to Accommodate the Impact

5.3.1 Infrastructural Changes

The continuous enhancement of big data analysis for incident forecasting (Payalan and Gauvensan, 2020), the development of computer vision and sensor algorithms (environment, degradation, V2V, and V2I communication) (Anderson et al., 2016), and the improvement of V2V and V2I communication (Fagnant and Kockelman, 2015) are the most important infrastructure changes. Partially CAVs profoundly affect the transportation network and travel patterns (Litman, 2023). CAVs sensors use radar, light detection and ranging (LiDAR), or video processing to identify vehicles in the traffic stream (Greer et al., 2018; Olia et al., 2018). In this context, studying the expected changes needed in the infrastructure is important.

Dedicated short range communication (DSRC) operates at 75 MHz bandwidth in the 5.9 GHz band, which the Federal Communications Commission (FCC) assigned in 2004 (Qi et al., 2020). DSRC allows vehicles to share their location information 10 times per second with a data rate of 3-27 Mbps (Bilgin and Gungor, 2013). 5G can provide speeds up to 10 gigabytes per second (Finley and Pearlstein, 2020). DSRC is a better option from a safety standpoint, while long-term evolution (LTE) is a better option for communicating non-safety information (Xu et al., 2017). 5G communication systems could improve system performance, enhance the user experience, and extend cellular communication applications. It is expected to be the most significant breakthrough in the development of car networking (Yang and Hua, 2019).

In order to understand the projected timelines, it is vital to point out which specific technological advancements could have the most significant impact on the deployment of CAVs. Practitioners and industry experts were asked about the technology which would have minimal impact on the current transportation infrastructure, and the results are shown in Figure 7.

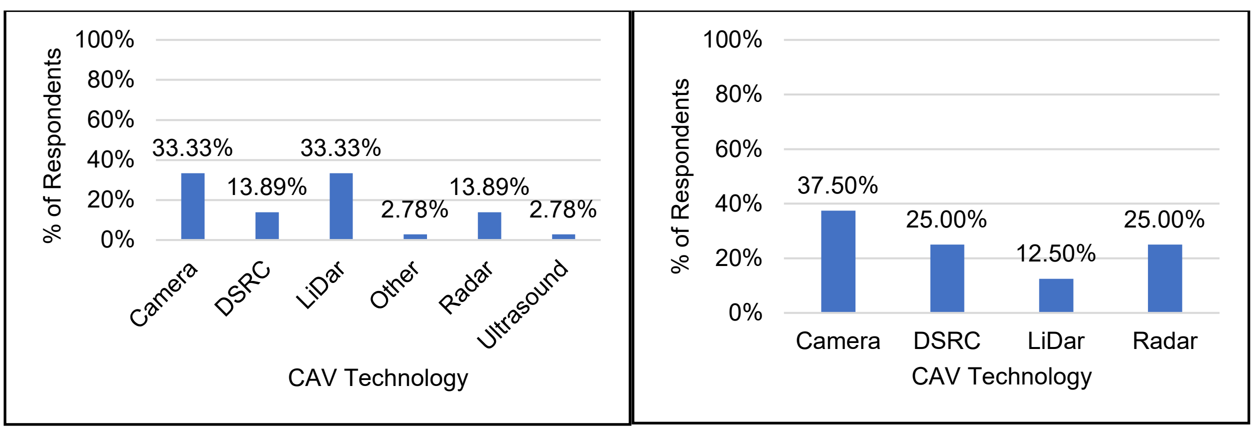


Figure 7 CAV technology that would have minimal impact on the current transportation infrastructure: (left) respondents are practitioners and (right) respondents are industry experts.

Figure 7 shows that about 33% of practitioners who responded to the survey think that cameras and LiDAR will have minimal impact, and about 38% of industry experts who responded to the survey think that cameras will have minimal impact on the current transportation infrastructure.

Practitioners were asked if the infrastructure elements should be upgraded or replaced with a radio frequency identification (RFID) or other sensors for communication if the CAV technology is not camera-based. About 83% of practitioners and 75% of industry experts who responded to the survey believed that current infrastructure should be upgraded with sensors to ensure seamless and safer movement of CAVs. Further, practitioners and industry experts were asked which traffic control devices should be upgraded or replaced with RFID or other sensors, and the results are summarized in Table 8.

Overall, there are conflicting opinions between practitioners and industry experts regarding updating traffic control devices. Practitioners agree that traffic control devices such as traffic signals, stop signs, yield signs, speed limit signs, pedestrian control signs, school zone signs, work-zone signs, and pavement markings should be upgraded. Industry experts perceive that only traffic signals should be updated with RFID or other sensors to ensure the safe movement of CAVs.

In addition to changes in traffic control devices, the provision of dedicated lanes for CAVs has been in discussion for a long time. About 25% of practitioners and 100% of industry experts who responded to the survey think CAVs require dedicated lanes. Nevertheless, 50% of practitioners who responded to the survey think CAVs will not require dedicated lanes.

Table 8 Required traffic control device to be upgraded

Traffic control device	% of Practitioners	% of IE
Traffic signals	81	100
Stop signs	75	25
Yield signs	63	25
Speed limit signs	63	50
High occupancy vehicle (HOV) lane signs	31	50
Bus lane signs	50	75
Toll/express road signs	62.5	25
Directional signs (for unconventional intersections like roundabouts)	50	50
Parking signs	31.25	25
Other regulatory signs (as per the MUTCD)	50	25
Pedestrian control and signs (walk zones, flashing beacons, pushbutton signs, etc.)	75	25
One-way/two-way signs	44	25
Lane addition/drop signs	19	25
Road curve ahead signs	37.5	50
Shoulder drop-off/no shoulder signs	31	25
Other warning signs (as per the MUTCD)	50	25
Information and guide signs (such as hospitals, rest areas, gas stations, etc.)	37.5	100
Pavement markings	50	25
Reflectors	31	50
School zone signs (pedestrian and traffic control)	81	25
Temporary traffic control signs (for work zone, severe weather, detouring, etc.)	62.5	50

5.3.2 Policy Changes

As mentioned previously, policies and regulations regarding CAVs are expected to be implemented in the United States in the next 5 to 20 years. However, how different they will be from the current policies and regulations is still a topic of interest to regulatory bodies and researchers. About 89% of practitioners and 100% of industry experts who responded to the survey think these policies and regulations for fully automated vehicles will differ from CAVs.

Regulatory bodies must restrict CAVs to certain areas/land use types to ensure seamless and safer navigation. The general perception of practitioners and industry experts on whether CAVs should be restricted to different land-use types was captured from the survey questions. Table 9 shows the percentage of practitioners and industry experts declining restrictions for the respective area type.

Table 9 % of respondents declining restrictions for the respective area type

Areas/land use	% of practitioners	% of Industry experts
Residential	82.35	100
Commercial	94.12	100
College	94.12	100
Industrial	94.12	100
School	88.24	100
Airport	94.12	100

Most practitioners and industry experts who responded to the survey think CAVs should not be restricted to any listed areas/land use types. However, some practitioners also expressed concern about using CAVs with vulnerable road users, such as in areas with high concentrations of pedestrians and bicyclists. Studies report that Level 1 and Level 2 CAVs are unsafe for vulnerable road users like pedestrians and bicyclists, and therefore, vulnerable road users should be segregated from the traffic by providing protected lanes to ensure their safety (Gajera et al., 2022, 2023).

Considering CAVs are an advanced technology, they may require specialized staffing for planning, designing, building, operating, and maintaining their transportation infrastructure. About 72% of practitioners and 50% of industry experts who responded to the survey agree on the requirement of specialized staffing in their respective organizations. Moreover, about 72% of practitioners and 50% of industry experts who responded to the survey think deploying CAV technology in their jurisdiction will require an additional component in annual budget allocation.

6. Data Readiness Framework

The preceding discussions show that CAVs are expected to transform transportation systems and societies. Effective large-scale planning for CAVs remains a challenge because of (a) the novelty of the technology, (b) uncertainties associated with the pace of technological change and adoption of CAVs, and (c) the uncertain impact of CAVs on travel demand, safety, roadway design, employment, and urban form. Moreover, the uncertainties could vary by type of travel (passenger or freight), functional class (highway or urban roads), and socioeconomic context. Due to these uncertainties, regulations and policies promoting desirable outcomes remain undefined or unclear. The communities must anticipate the trajectories of changes CAVs could affect and develop plans to accommodate these impacts.

With uncertainties associated with the continuous evolution of technology and the adoption of CAVs users, multiple scenarios (unimodal and multimodal scenarios) can be visualized. Each scenario would have varying impacts and, therefore, need different actions to accommodate the impacts. For instance, in the case of a unimodal scenario, congestion levels and VMT would be high due to higher private vehicle ownership, poor safety levels, poor accessibility and mobility, and higher inequities. Minimum infrastructural or road design changes would be required to accommodate these impacts. However, in the multimodal scenario, because of coordination in different modes, congestion and VMT would be lower, mobility and accessibility would improve, social inequities would be bridged, and safety levels would be higher. However, the infrastructure needs modifications and design changes to accommodate the multimodal transportation scenario.

Therefore, this section proposes a data readiness framework for fostering an integrated or inclusive CAVs environment. As discussed in the Introduction chapter, the team has proposed the data readiness framework considering four categories: (1) vehicle, (2) infrastructure, (3) data, and (4) public impression. The categories, their respective action items, recommendations, and priority for each action item in each category are summarized in Table 10. Moreover, a detailed readiness plan for large-scale planning that covers other essential aspects, such as planning and policy, is presented in Appendix A. The readiness plan discussed in Appendix A also contains information related to the responsible stakeholders, time horizon (priority of implementation), probable CAV adoption (penetration of CAV), and probable impact if the plan is implemented.

The data readiness framework proposed in Table 10 was discussed over two 90-minute brainstorming sessions. The brainstorming sessions included team members from UNC Charlotte, Appalachian State University, and HSRC-UNC Chapel Hill, and were conducted online via Zoom platform, recorded (upon the consent of participants), and summarized. Based on the discussion, items that exclusively would influence North Carolina and are under the purview of agencies in North Carolina are considered. In addition to the readiness plan discussed in Table 10, a summary of data that NCDOT should focus on collecting and maintaining s presented in Table 11.

Table 10 Data readiness framework

Category	Action Item	General Description and Recommendation	Priority
Vehicle	Vehicle Registration	Stakeholders should emphasize exploring vehicle registration methods that assist in identifying vehicle-level data. • Separate vehicle registration for different levels of CAVs and vehicle types. • Explore advanced registration methods like equipping vehicle registration plates with high-security RFID-based sensor tags. Sensors in the infrastructure can read the tags to capture vehicle trip-related information.	High (short-term)
	Vehicle Testing	Focus should be placed on testing vehicles and their in-vehicle features. • Call for periodic testing of the vehicle and its features. • Collaborate with vehicle manufacturers to ensure that sales personnel and owners know how different in-vehicle features operate and how they impact.	
	Permits	Stakeholders should focus on developing licensing or permit procedures. • Revisit the age limit for issuing driving permits based on the level of CAV. • Revise the procedure for issuing the license or driving permit based on the level of CAV.	
Infrastructure	Traffic Signs	Computer vision system of CAVs is responsible for reading and interpreting the surrounding traffic environment. Stakeholders should emphasize updating traffic signs so that CAVs can read and interpret traffic signs accurately and maneuver safely through the traffic. • Application of RFID-based sensors can be explored. They can be placed on traffic signs to ensure CAVs accurately read and interpret traffic signs and accordingly make decisions. The application of sensors can be particularly effective under adverse weather conditions where the visibility is poor and the effectiveness of computer-vision systems subsides. • Rural areas may pose significant challenges because of lack of infrastructure. • Regulatory and warning signs should be prioritized over other type of signs. • Explore the relationship between visibility, connectivity and CAV operations.	High (short-term)
	Traffic Signals and Intersections	Stakeholders should emphasize updating traffic signals and intersections. • Roadside units (RSUs) that can effectively communicate with CAVs using wireless technology can be installed at intersections and traffic signals to ensure smoother and safer	

Category	Action Item	General Description and Recommendation	Priority
		travel. CAVs can communicate with RSUs installed at traffic signals and intersections and optimize their trajectory. • Digitization of road networks and installation of wireless technology should be done simultaneously.	
	Road Markings	Stakeholders should focus on updating road makings as CAVs need clear marking to function properly. Improper delineation of road markings poses challenges for vision sensors of CAVs to predict the vehicle's position in the lane. The effectiveness of the lane keep assist (LKA) or lane centering (LC) feature of CAVs would depend on the readability of road markings. • Increasing the width or thickness of road markings can ensure better readability. • Explore advanced options such as magnetic and retro-reflective paints and sensors embedded in the pavement to improve the positioning and navigation of CAVs. • Digitize road infrastructure. CAVs can read digitized maps to navigate safely. • Solar-powered connected cat eyes can be installed to ensure better readability of road marking by CAVs. • Revisit maintenance standards and frequency.	
	Pavement Surface Condition	CAVs are likely to have precise steering control, and therefore, the vehicle would be maintained in the center of the lane via LC or LKA. Continuous center lane position could increase point load and lead to quick pavement deterioration. • Investigate the effect of CAVs on pavement deterioration and establish a trade-off between speed limit, number of lanes, and pavement deterioration. • Research how pavement friction will influence the performance of CAVs in terms of rear-end and lane-change crashes. Although CAVs can interact with other vehicles via V2V and V2I communications, the probability of hard barking will reduce.	Low (long-term)
	Lighting	Adequate illumination, especially on urban roads, is essential during night hours to ensure road safety for all users. • Emphasize improving lighting facilities, i.e., illuminance and spacing. • Investigate the need for lighting standards for effective and safe CAVs, particularly under adverse weather conditions.	Moderate (medium-term)
	Assessment and Maintenance of Infrastructure	Maintenance of road infrastructures is essential for ensuring the safe and smooth movement of CAVs and the safety of other road users.	High (short-term)

Category	Action Item	General Description and Recommendation	Priority
		• Adopt a digitized infrastructure assessment methodology. LiDAR sensors and artificial intelligence-based video analytics can be explored to assess infrastructures condition. • Develop a periodic schedule for the inspection and maintenance of infrastructure. • Allocate funds to assess and maintain infrastructure for developing a CAV-inclusive infrastructure.	
	Digitize Road Infrastructure	Digitize existing road infrastructure in addition to making modifications to the existing infrastructure. CAVs can use the digitized road infrastructure map to navigate. The digitized maps will ensure a CAV-inclusive transportation system if integrated with updated infrastructure. • Adopt LiDAR sensors to scan and assess existing road infrastructure. • Periodically update the digitized road maps. • Information related to work-zone, road closures, and special events should be updated on the digitized maps.	
	Prioritize Right-of-Way for Vulnerable Road Users	Vulnerable road users such as pedestrians, cyclists, motorcyclists, and e-scooters are the biggest obstacle to the success of the collision avoidance system of CAVs. • Test CAV technology and interactions with pedestrians or other object detection under varying weather conditions. • Prioritize improvements in pedestrian infrastructure. • Separate vulnerable road users from CAVs traffic by providing separate lanes. • If separate bike lanes cannot be provided, then temporary or flexible lanes for cycling could be provided. The temporary bike lanes can be installed using movable barriers. • Install smart cameras at locations with higher densities of pedestrians and bicyclists and develop robust detection algorithms so that the information related to the presence and volume of vulnerable road users can be relayed to CAVs.	
	Street Redesign	Since CAVs have the potential to accurately steer, control, and track the vehicle precisely within a lane, the road can be redesigned. • Lane widths can be reduced; automobile lanes can be narrowed in favor of non-motorized and public transportation. • Plan for a road diet and tighter corner radii. • Maintain emergency lanes as CAVs could need them under software or hardware failures and	Moderate (medium-term)

Category	Action Item	General Description and Recommendation	Priority
		extreme weather conditions as the drivers need to take control of the vehicle. • Plan, establish, and demarcate precise CAV pickup and drop-off locations.	
	Modify/Adapt Speed Limits	Speed is one of the risk factors influencing the severity of crashes. CAVs are expected to comply with the speed limits; therefore, the proportion of crashes resulting from human errors and over speeding will be reduced significantly. • Revise speed limits. Adopt a lower speed limit to reduce the risk of crashes and crash severity. • Implement variable speed limit strategy. • Continuous changes in the speed limit of the road may be difficult for CAVs to be ready. Digitizing road maps can aid CAVs in adjusting to the changes in speed limit. • Emphasize equipping speed limit signs with sensors for communication, ensuring safer movement.	
	Add Vehicle Charging Stations	CAVs are expected to be electric vehicles. • Add vehicle charging stations around regions and at hotspot locations. • Collaborate with research institutions in deciding the optimal number and location of charging stations. • Collaborate with research institutions to explore options for updating infrastructure with charging abilities rather than adding charging stations.	
	Smart Intersections	Stakeholders should focus on designing and deploying smart intersections. • Design adaptive and coordinated traffic signal control. • Install RSUs and deploy wireless technology for communication of CAVs with smart intersections.	
Data	Data Standardization, Storage, Data Sharing, and Privacy	Stakeholders should focus on establishing standards for data. • Establish standards for the third party to collect and report data. • Establish a data repository for storing and sharing data. • Establish a systematic methodology to archive data. • Coordinate with the Department of Information Technology for data and cyber security. • Establish data-sharing standards.	High (short-term)
Public Impression	Education of Staff	Facilitate staff training. • In-house training or training at institutes should be arranged. The training would ensure that staff knows how connectivity and automation technologies impact transportation infrastructure and societies.	High (short-term)

Category	Action Item	General Description and Recommendation	Priority
		• Collaborate with practitioners from different departments.	
	Education and Awareness Programs for the General Public	• To ensure a better reception of CAVs by the public, stakeholders should plan to organize education and awareness programs for the public. This would ensure that the public knows CAV technology and its potential impacts. • Education and awareness programs should be arranged periodically.	

Table 11 Data to be collected and maintained by NCDOT

Road Inventory Data	• Collect detailed road inventory data. Use LiDAR sensors to collect road inventory data. • Road inventory data should contain information related to the speed limit, type of intersection and its characteristics (signal cycle time for signalized), stop signs, speed limit signs, pavement marking, bus stops, bus bays, pedestrian crossings, bicycle lanes and marking, number of lanes, AADT, shoulders, median type, turning lanes, railroad crossings, road alignment and grade, public transportation routes and stations, and functional class of road. • Update existing databases.
Operations	• Collect data related to vehicle type and level of autonomy. • For mobility-related analysis, collect AADT, traffic volume, and travel time data by vehicle type and level of autonomy. Contractual agreements with respective third-party such as Wejo, StreetLight, INRIX, HERE, etc. should be made. The third part will be responsible for collecting and reporting data. • Collect weather data and connect with travel time and volume data. • Collect and store micro-level data, i.e., vehicle trajectories.
Crashes	• Collect precise crash data. In addition to the individual and crash-related characteristics, record information related to vehicle characteristics (i.e., vehicle type, level of autonomy, and in-vehicle features). • Collect and record data regarding the disengagement of autonomous features. This is essential in the case of handling legal disputes related to crash insurance. • Collect information related to communication of CAVS with infrastructure.
Collect Users Trip Level Data Using The Trip Diary	• Collect users' sentiment, willingness to use, and willingness to pay data for CAVs, SAVs, and automated transit. • Develop an activity diary and encourage users to record trip-related data through activity dairy.

7. Implementation and Technology Transfer Plan

This project aimed to provide NCDOT with actionable data on the state of knowledge and opinions about CAVs among transportation professionals and industry experts. The products from this project flow from interviews and the survey.

7.1 Products

7.1.1 Key Informant Interview Component

- Peer-reviewed paper (currently in preparation)
- Master's thesis, T. Schado—July 2023
- Interview instrument

7.1.2 Survey Component—Young People and CAVs

- Peer-reviewed paper: Bagli, Shay, and Combs, *Transportation Research Record,* TRB, 2022
- Master's thesis, H. Bagli—May 2021
- Survey instrument

7.1.3 Survey Component—Practitioners and Industry Experts

- Survey instrument
- Descriptive statistics

7.1.4 Data Readiness Framework

- Readiness framework for effective large-scale planning for CAVs
- List of Data to be collected and maintained by NCDOT

7.2 NCDOT Relevance

The analysis of key informants' perceptions and opinions on CAVs and associated data concerns are useful to transportation professionals as evidence of existing professional knowledge within the state, highlighting how the DOT can prepare for CAVs through both in-house activities and in partnership with municipalities, counties, and MPOs/RPOs. Transportation Panning, Civil Rights, Public Involvement, and other units may find the analysis useful in preparing the state's roads and streets to increase CAVs' penetration and interactions with conventional vehicles and non-motorized travelers. The DOT and local governments alike can anticipate that the arrival of CAVs may usher in excitement and appreciation for their potential benefits and concerns—among the public and transportation professionals—about data privacy and security and their impacts on communities.

This project supported several students as research assistants and produced data that supported two master's theses. Students worked on designing rubrics for selecting locations, recruiting key informants, and designing strong survey and interview instruments rooted firmly in the methodological literature for qualitative research methods.

7.3 Training for Implementation

The instruments created during this project may be used or adapted by NCDOT experts or other transportation professionals, with no formal training required, although the team welcomes inquiries.

References

AAA. (2019). Fact sheet: Vehicle technology survey-phase IV. Retrieved from https://newsroom.aaa.com/tag/self-driving-cars/.

Allessandrini, A., Bartoli, M., Bellucci, M. A., and Fazio, C. (2015). Automated vehicles and the rethinking of mobility and cities. Transportation Research Procedia, 5, 145–160.

Anderson, J. M., Kalra, N. S., Sorensen, P., Samaras, C., and Oluwatola, T. A. (2016). Autonomous Vehicle Technology: A Guide for Policymakers. CA: RAND Corporation. Retrieved from https://www.rand.org/pubs/research_reports/RR443-2.html

Asgari, H., and Jin, X. (2019). Incorporating attitudinal factors to examine adoption of and willingness to pay for autonomous vehicles. Transportation Research Record: Journal of the Transportation Research Board, 2673(8), 418–429.

Bagli, H., Shay, E., and Combs, T. (2022). Automated vehicles: Use, share, own? Young adults' perceptions of automated vehicles. Transportation Research Record, 2022.

Bansal, P., and Kockelman, K. M. (2018). Are we ready to embrace connected and self-driving vehicles? A case study of Texans. Transportation, 45, 641–675. doi:https://doi.org/10.1007/s11116-016-9745-z

Barth, M., and Shaheen, S. A. (2002). Shared-use vehicles systems: Framework for classifying carsharing, station cars, and combined approaches. Transportation Research Record, 1791(1), 105–112.

Benkraouda, O. L., and Chakraborty, A. (2022). Policies and design guidelines to plan for connected and autonomous vehicles. University of Illinois Urbana-Champaign. doi:https://doi.org/10.36501/0197-9191/22-012

Berliner, R. M., Hardman, S., and Tal, G. (2019). Uncovering early adopter's perceptions and purchase intentions of automated vehicles: Insights from early adopters of electric vehicles in California. Transportation Research Part F: Traffic Psychology and Behaviour, 60, 712–722.

Besen-Cassino, Y., and Cassino, D. (2018). Social research methods by example: Applications in the modern world. Routledge.

Bilal, M. T., and Giglio, D. (2023). Analysing inequity in land use and transportation models by genetic algorithm for realistically quantified penetration rate of advanced driving system equipped vehicles. Transportation Research Interdisciplinary Perspectives, 20, 100841. doi:https://doi.org/10.1016/j.trip.2023.100841

Bilgin, B. E., and Gungor, V. C. (2013). Performance comparison of IEEE 802.11 p and IEEE 802.11 b for vehicle-to-vehicle communications in highway, rural, and urban areas. International Journal of Vehicular Technology, 2013, 2013:1-10.

Booth, L., Norman, R., and Pettigrew, S. (2019). The potential implications of autonomous vehicles for active transport. Journal of Transport and Health, 15, 100623. doi:https://doi.org/10.1016/j.jth.2019.100623

Bösch, P. M., Ciari, F., and Axhausen, K. W. (2018). Transport policy optimization with autonomous vehicles. Transportation Research Record, 2672(8), 698–707. doi:https://doi.org/10.1177/0361198118791391

Bouualouache, A., Brik, B., Tang, Q., Korba, A. A., Cherrier, S., Senouci, S.-M., Pardo, E., Ghamri-Doudane, Y., Langar R., and Engel, T. (2023). 5G vehicle-to-everything at the cross-borders: Security challenges and opportunities. IEEE, Internet of Things Magazine,6(1), 114-119. doi:10.1109/IOTM.001.2200140

Brell, T., Philipsen, R., and Ziefle, M. (2018). sCARy! Risk perceptions in autonomous driving: The influence of experience on perceived benefits and barriers. Risk Analysis, 39(2), 342–357.

Buhr, S. (2017, July 21). Lyft launches a new self-driving division and will develop its own autonomous ride-hailing technology. TechCrunch. Retrieved from https://techcrunch.com/2017/07/21/lyft-launches-a-new-self-driving-division-called-level-5-will-develop-its-own-self-driving-system/.

Burghard, U., and Dütschke, E. (2019). Who wants shared mobility? Lessons from early adopters and mainstream drivers on electric carsharing in Germany. Transportation Research Part D: Transport and Environment, 71, 96–109. doi:https://doi.org/10.1016/j.trd.2018.11.011

Campbell, H. (2018). Who will own and have propriety over our automated future? Considering governance of ownership to maximize access, efficiency, and equity in cities. Transportation Research Record, 2672(7), 14-23.

Cepolina, E. M., and Farina, A. (2013). A methodology for planning a new urban car sharing system with fully automated personal vehicles. European Transport Research Review, 6(2), 191–204.

Charness, N., Yoon, J. S., Souders, D., Stothart, C., and Yehnert, C. (2018). Predictors of attitudes toward autonomous vehicles: The roles of age, gender, prior knowledge, and personality. Frontiers in Psychology, 9.

Clements, L. M., and Kockelman, K. M. (2017). Economic effects of automated vehicles. Transportation Research Record, 2606(1), 106-114.

Cohen, B. D., and Kietzman, J. (2014). Ride on! Mobility business models for the sharing economy. Organization and Environment, 27(3), 279–296.

Cohen, T., and Cavoli, C. (2019). Automated vehicles: exploring possible consequences of government (non)intervention for congestion and accessibility. Transport Reviews, 31(1). doi:https://doi.org/10.1080/01441647.2018.1524401

Cucor, B., Petrov, T., Kamencay, P., Pourhashem, G., and Dado, M. (2022). Physical and digital infrastructure readiness index for connected and automated vehicles. Sensors, 22(19), 7315. doi:https://doi.org/10.3390/s22197315

Currie, G. (2018). Lies, damned lies, AVs, shared mobility, and urban transit futures. Journal of Public Transportation, 21(1), 19–30.

Dey, K., Rayamajhi, A., Chowdhury, M., and Bhavsar, P. (2016). Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in a heterogeneous wireless network –

Performance evaluation. Transportation Research Record Part C: Emerging Technologies, 68(6). doi:https://doi.org/10.1016/j.trc.2016.03.008

Dias, F. F., Lavieri, P. S., Garikapati, V. M., Astroza, S., Pendyala, R. M., and Bhat, C. R. (2017). A behavioral choice model of the use of car-sharing and ride-sourcing services. Transportation, 44(6), 1307–1323.

Dillman, D. A., Smyth, J. D., and Christian, L. M. (2014). Internet, phone, mail, and mixed-mode surveys: The tailored design method. Wiley.

Dowling, R., Kent, J. L., and Höchtl, J. (2018). Sharing as sociomaterial practice: Car sharing and the material reconstitution of automobility. Geoforum, 88, 10–16.

Duarte, F., and Ratti, C. (2018). The impact of autonomous vehicles on cities: A review. Journal of Urban Technology, 25(4), 3–18. doi:https://doi.org/10.1080/10630732.2018.1493883

Fagnant, D. J., and Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167-181. doi:https://doi.org/10.1016/j.tra.2015.04.003

Faisal, A., Yigitcanlar, T., Kamruzzaman, M., and Currie, G. (2019). Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy. Journal of Transport and Land Use, 12(1). doi:https://doi.org/10.5198/jtlu.2019.1405

Finley, K., and Pearlstein, J. (2020). The wired guide to 5G. Retrieved from https://www.wired.com/story/wired-guide-5g/.

Fitch, G. M., Bowman, D. S., and Llaneras, E. (2014). Using wizard of Oz technique to evaluate connected vehicles: Distracted driver performance to multiple alerts in a multiple-conflict scenario. In 93rd Annual Meeting of Transportation Research Board. Washington, DC.

Fraedrich, E., Heinrichs, D., Bahamonde-Birke, F. J., and Cyganski, R. (2019). Autonomous driving, the built environment and policy implications. Transportation Research Part A—Policy and Practice, 122, 162–172. doi:https://doi.org/10.1016/j.tra.2018.02.018

Fulton, L., Mason, J., and Meroux, D. (2017). Three revolutions in transportation. UC Davis. Retrieved from https://itspubs.ucdavis.edu/publication_detail.php?id=2723.

Gajera, H., Pulugurtha, S. S., and Mathew, S. (2022). Influence of level 1 and level 2 automated vehicles on fatal crashes and fatal crash occurrence. Mineta Transportation Institute Publications. https://doi.org/10.31979/mti.2022.2034

Gajera, H., Pulugurtha, S. S., Mathew, S., and Bhure, C. M. (2023). Synthesizing fatal crashes involving partially automated vehicles and comparing with fatal crashes involving non-automated vehicles. Transportation Engineering, 12, 100178.

Genders, W., and Razavi, S. N. (2016). Impact of connected vehicle on work zone network safety through dynamic route guidance. Journal of Computing in Civil Engineering, 30(2), 04015020.

Gkartzonikas, C., and Gkritza, K. (2019). What have we learned? A review of stated preference and choice studies on autonomous vehicles. Transportation Research Part C: Emerging Technologies, 98, 323–337.

Golub, A., Satterfield, V., Serritella, M., Singh, J., and Phillips, S. (2019). Assessing the barriers to equity in smart mobility systems: A case study of Portland, Oregon. Case Studies on Transport Policy, 7(4), 689-697. doi:https://doi.org/10.1016/j.cstp.2019.10.002

Greer, L., Fraser, J. L., Hicks, D., Mercer, M., and Thompson, K. (2018). Intelligent transportation systems benefits, costs, and lessons learned: 2018 update report. Publication # FHWA-JPO-18-641, United States Department of Transportation, ITS Joint Program Office.

Gurumurthy, K. M., Kockelman, K. M., and Simoni, M. D. (2019). Benefits and costs of ride-sharing in shared automated vehicles across Austin, Texas: Opportunities for congestion pricing. Transportation Research Record, 2651(1), 548–556. doi:https://doi.org/10.1177/0361198119850785

Gyergyay, B., Gomari, S., Friedrich, M., Sonnleitner, J., Olstam, J., and Johansson, F. (2019). Automation-ready framework for urban transport and road infrastructure planning. Transportation Research Procedia, 41, 88-97. doi:https://doi.org/10.1016/j.trpro.2019.09.018

Hardman, S., Berliner, R., and Tal, G. (2019). Who will be the early adopters of automated vehicles? Insights from a survey of electric vehicle owners in the United States. Transportation Research Part D: Transport and Environment, 71, 248–264.

Hasnat, M. M., Bardaka, E., and Samandar, M. S. (2023). Differential impacts of autonomous and connected-autonomous vehicles on household residential location. Travel Behaviour and Society, 32, 100570. doi:https://doi.org/10.1016/j.tbs.2023.02.007

Hörl, S. (2016). Implementation of an autonomous taxi service in a multi-modal traffic simulation using Matsim. Master thesis in Complex Adaptive Systems, Chalmers University of Technology.

Hubbard, S. M. L. (2018). Automated vehicle legislative issues. Transportation Research Record, 2672(7), 1–13.

Jiang, L., Chen, H., and Chen, Z. (2022). City readiness for connected and autonomous vehicles: A multi-stakeholder and multi-criteria analysis through analytic hierarchy process. Transport Policy, 128, 13-24. doi:https://doi.org/10.1016/j.tranpol.2022.09.012

Jin, S. T., Kong, H., Wu, R., and Sui, D.Z. (2018). Ridesourcing, the sharing economy, and the future of cities. Cities, 76, 96–104.

Kang, N.-Y., and Kim, Y. (2019). Potential of urban land use by autonomous vehicles: Analyzing land use potential in Seoul capital area of Korea. IEEE Access, 7. doi:https://doi.org/10.1109/ACCESS.2019.2929777

Khan, J. A., Wang, L., Jacobs, E., Talebian, A., Mishra, S., Santo, C. A., Golias, M., and Astorne-Figari, C. (2019). Smart cities connected and autonomous vehicles readiness index. The 2nd ACM/EIGSCC Symposium. doi:https://doi.org/10.1145/1122445.1122456

Khan, S. K., Shiwakoti, N., Stasinopoulos, P., and Warren, M. (2022). Modelling cybersecurity regulations for automated vehicles. Accident Analysis and Prevention, 186, 107054. doi:https://doi.org/10.1016/j.aap.2023.107054

Kolarova, V., Steck, F., and Bahamonde-Birke, F. J. (2019). Assessing the effect of autonomous driving on value of travel time savings: A comparison between current and future preferences. Transportation Research Part A: Policy and Practice, 129, 155-169. doi:https://doi.org/10.1016/j.tra.2019.08.011

Krueger, R., Rashidi, T. H., and Rose, J. M. (2016). Preferences for shared autonomous vehicles. Transportation Research Part C: Emerging Technologies, 69, 343–355.

Lee, Y.-C., and Mirman, J. H. (2018). Parents' perspectives on using autonomous vehicles to enhance children's mobility. Transportation Research Part C: Emerging Technologies, 96, 415–431.

Lim, H. S., and Taeihagh, A. (2018). Autonomous vehicles for smart and sustainable cities: An in-depth exploration of privacy and cybersecurity implications. Energies, 11(2), 1062. doi:https://doi.org/10.3390/en11051062

Lim, W., Lee, S., Sung, B., and Cronin, S. (2023). Is Australia ready for autonomous vehicles? Examining the factors influencing AV adoption through expert interviews. Australasian Marketing Journal. doi:https://doi.org/10.1177/14413582231175152

Litman, T. (2023). Autonomous vehicle implementation predictions: Implications for transport planning. Victoria Transport Policy Institute. Retrieved from https://www.vtpi.org/avip.pdf.

Liu, J., Kockelman, K. M., Boesch, P. M., and Ciari, F. (2017). Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based simulation. Transportation, 44(6), 1261-1278.

Liu, P., Yang, R., and Xu, Z. (2018). Public acceptance of fully automated driving: Effects of social trust and risk/benefit perceptions. Risk Analysis, 39(2), 326–341.

Liu, P., Du, Y., and Xu, Z. (2019). Machines versus humans: People's biased responses to traffic accidents involving self-driving vehicles. Accident Analysis and Prevention, 125, 232–240.

Loeb, B., Kockelman, K. M., and Liu, J. (2018). Shared autonomous electric vehicle (SAEV) operations across the Austin, Texas Network with charging infrastructure decisions. Transportation Research Part C: Emerging Technologies, 89, 222-233.

Loke, S. W., and Aliedani, A. (2018). On cooperative autonomous vehicles in the urban environment: Issues and challenges for dropping-off and parking. In 2018 IEEE 4th World Forum on Internet of Things (WF-IoT) (pp. 615-618).

Merfeld, K., Wilhelms, M.-P., Henkel, S., and Kreutzer, K. (2019). Carsharing with shared autonomous vehicles: Uncovering drivers, barriers and future developments – A four-stage Delphi study. Technological Forecasting and Social Change, 144, 66–81.

Merriam, S. B. (2009). Qualitative research: A guide to design and implementation. Wiley.

Metz, D. (2018). Developing policy for urban autonomous vehicles: Impact on congestion. Urban Science, 2(2), 33.

Meyer, J., Becker, H., Bösch, P. M., and Axhausen, K. W. (2017). Autonomous vehicles: The next jump in accessibilities? Research in Transportation Economics, 62 (2017), 80-91. doi:https://doi.org/10.1016/j.retrec.2017.03.005

Milanés, V., and Shladover, S. E. (2014). Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data. Transportation Research Part C: Emerging Technologies, 48, 285-300.

Millard-Ball, A. (2019). The Autonomous vehicle parking problem. Transport Policy, 75, 99-108.

Morando, M. M., Tian, Q., Truong, L. T., and Vu, H. L. (2018). Studying the safety impact of autonomous vehicles using simulation-based surrogate safety measures. Journal of Advanced Transportation, Article ID 6135183, 11 pages. https://doi.org/10.1155/2018/6135183.

Nazari, F., Noruzoliaee, M., and Mohammadian, A. (2018). Shared versus private mobility: Modeling public interest in autonomous vehicles accounting for latent attitudes. Transportation Research Part C: Emerging Technologies, 97, 456–477.

Nodjomian, A., and Kockelman, K. (2019). How does the built environment affect interest in the ownership and use of self-driving vehicles? Journal of Transport Geography, 78, 115–134. doi:https://doi.org/10.1016/j.jtrangeo.2019.05.016

O'Hern, S., and Louis, R. S. (2023). Technology readiness and intentions to use conditionally automated vehicles. Transportation Research Part F: Traffic Psychology and Behaviour, 94, 1-8. doi:https://doi.org/10.1016/j.trf.2023.02.001

Olia, A., Razavi, S., Abdulhai, B., and Abdelgawad, H. (2018). Traffic capacity implications of automated vehicles mixed with regular vehicles. Journal of Intelligent Transportation Systems, 22(3), 244-262.

Pakusch, C., Stevens, G., Boden, A., and Bossauer, P. (2018b). Unintended effects of autonomous driving: A study on mobility preferences in the future. Sustainability, 10(7), 2404.

Pakusch, C., Stevens, G., and Bossauer, P. (2018a). Shared autonomous vehicles: Potentials for sustainable mobility and risks of unintended effects. EPiC Series in Computing, 52, 258–269.

Panagiotopoulos, I., and Dimitrakopoulos, G. (2018). An empirical investigation on consumers' intentions towards autonomous driving. Transportation Research Part C: Emerging Technologies, 95, 773–784.

Payalan, Y. F., and Guvensan, M. A. (2019). Towards next-generation vehicles featuring the vehicle intelligence. IEEE Transactions on Intelligent Transportation Systems, 21(1), 30 - 47. doi:https://doi.org/10.1109/TITS.2019.2917866

Pettigrew, S., Fritschi, L., and Norman, R. (2019). The potential implications of autonomous vehicles in and around the workplace. International Journal of Environmental Research and Public Health, 15(9), 1876. doi:https://doi.org/10.1109/TITS.2019.2917866

Pettigrew, S., Dana, L. M., and Norman, R. (2019). Clusters of potential autonomous vehicle users according to propensity to use individual versus shared vehicles. Transport Policy, 76, 13–20.

Qi, W., Landfeldt, B., Song, Q., Guo, L., and Jamalipour, A. (2020). Traffic differentiated clustering routing in DSRC and C-V2X hybrid vehicular networks. IEEE Transactions on Vehicular Technology, 69(7), 7723-7734.

Rahman, M. M., and Thill, J.-C. (2023). Impacts of connected and autonomous vehicles on urban transportation and environment: A comprehensive review. Sustainable Cities and Society, 96, 104649. doi:https://doi.org/10.1016/j.scs.2023.104649

Raue, M., D'Ambrosio, L. A., Ward, C., Lee, C., Jacquillat, C., and Coughlin, J. F. (2019). The influence of feelings while driving regular cars on the perception and acceptance of self-driving cars. Risk Analysis, 39(2), 358–374.

Russell, J. (Year). China's Didi Chuxing opens U.S. lab to develop AI and self-driving car tech. TechCrunch. Retrieved from https://techcrunch.com/2017/03/08/didi-us-research-lab/.

SAE. (2021, May 3). SAE levels of driving automation™ refined for clarity and international audience. Retrieved July 7, 2023, from https://www.sae.org/blog/sae-j3016-update

Singh, M. K., Haouari, R., Papazikou, E., Sha, H., Quddus, M., Chaudhry, A., Thomas, P., and Morris, A. (2023). Examining parking choices of connected and autonomous vehicles. Transportation Research Record. doi:https://doi.org/10.1177/03611981231166383

Soteropoulos, A., Berger, M., and Ciari, F. (2019). Impacts of automated vehicles on travel behaviour and land use: An international review of modelling studies. Transport Reviews, 39(1). doi:https://doi.org/10.1080/01441647.2018.1523253

Spurlock, C. A., Sears, J., Wong-Parodi, G., Walker, V., Jin, L., Taylor, M., Duvall, A., Gopal, A., and Todd, A. (2019). Describing the users: Understanding adoption of and interest in shared, electrified, and automated transportation in the San Francisco Bay Area. Transportation Research Part D: Transport and Environment, 71, 283–301. doi:https://doi.org/10.1016/j.trd.2019.01.014

Stewart, D. W., Shamdasani, P. N., and Rook, D. W. (2007). Focus groups: Theory and practice (2nd ed.). SAGE Publications.

Stocker, A., and Shaheen, S. (2017). Shared automated vehicles: Review of business models. International Transport Forum, Discussion Paper No. 2017-09.

Stoiber, T., Schubert, I., Hoerler, R., and Paul, B. (2019). Will consumers prefer shared and pooled-use autonomous vehicles? A stated choice experiment with Swiss households. Transportation Research Part D: Transport and Environment, 71, 265-282. doi:https://doi.org/10.1016/j.trd.2018.12.019

Szimba, E., and Hartmann, M. (2020). Assessing travel time savings and user benefits of automated driving – A case study for a commuting relation. Transport Policy, 98, 229-237. doi:https://doi.org/10.1016/j.tranpol.2020.03.007

Taeihagh, A., and Lim, H. S. (2019). Governing autonomous vehicles: Emerging responses for safety, liability, privacy, cybersecurity, and industry risks. Transport Reviews, 39(1).

Taiebat, M., Stolper, S., and Xu, M. (2019). Forecasting the impact of connected and automated vehicles on energy use: A microeconomic study of induced travel and energy rebound. Applied Energy, 247, 297–308. doi:https://doi.org/10.1016/j.apenergy.2019.03.174

Talebian, A., and Mishra, S. (2018). Predicting the adoption of connected autonomous vehicles: A new approach based on the theory of diffusion of innovations. Transportation Research Part C: Emerging Technologies, 95, 363–380.

Talebpour, A., and Mahmassani, H. S. (2016). Influence of connected and automated vehicles on traffic flow stability and throughput. Transportation Research Part C: Emerging Technologies, 71, 143-163.

Teale, C. (2020), Poll: 3 in 4 Americans say AV tech 'not ready for primetime'. Smart cities Dive. https://www.smartcitiesdive.com/news/poll-3-in-4-americans-say-av-tech-not-ready-for-primetime/578355/

Tengilimoglu, O., Carsten, O., and Wadud, Z. (2023). Implications of automated vehicles for the physical road environment: A comprehensive review. Transportation Research Part E: Logistics and Transportation Review, 169, 102989. doi:https://doi.org/10.1016/j.tre.2022.102989

Tian, L. J., Sheu, J. B., and Huang, H. J. (2019). The morning commute problem with endogenous shared autonomous vehicle penetration and parking space constraint. Transportation Research Part B: Methodological, 123, 258-278.

Underwood, S. E., Marshall, S., and Niles, J. (2014). An assessment of emerging transportation technologies and a policy roadmap for more sustainable transportation. Graham Environmental Sustainability Institute. Retrieved from https://graham.umich.edu/media/files/LC-IA-Final-Underwood.pdf.

Vassallo, E. W., and Manaugh, K. (2018). Spatially clustered autonomous vehicle malware: Producing new urban geographies of inequity. Transportation Research Record, 2671(1), 66–75. doi:https://doi.org/10.1177/0361198118794057

Wagner, I. (2019). Connected cars worldwide-statistics and facts. Retrieved from https://www.statista.com/topics/1918/connected-cars/#topicOverview.

Watkins, S. J. (2018). Driverless cars – advantages of not owning them: Car share, active travel and total mobility. Proceedings of the Institution of Civil Engineers - Municipal Engineer, 171(1), 26–30.

Whittle, C., Whitmarsh, L., Haggar, P., Morgan, P., and Parkhurst, G. (2019). User decision-making in transitions to electrified, autonomous, shared or reduced mobility. Transportation Research Part D: Transport and Environment, 71, 302–319.

World Bank (2021). Do speed limit reductions help road safety? Lessons from the Republic of Korea’s Recent move to lower speed limit on urban roads. Mobility and Transport Connectivity Series. Retrieved from https://openknowledge.worldbank.org/server/api/core/bitstreams/98665ccb-8c76-5ed8-8434-20f43729ed9e/content.

Xu, Z., Li, X., Zhao, X., Zhang, M. H., and Wang, Z. (2017). DSRC versus 4G-LTE for connected vehicle applications: A study on field experiments of vehicular communication performance. Journal of Advanced Transportation, 2017, 2017, 1-10.

Yadan, L. (2019). From transportation infrastructure to green infrastructure—adaptable future roads. Landscape Architecture Frontiers, 7(2), 92-99. doi:https://doi.org/10.15302/J-LAF-20190209

Yang, Y., and Hua, K. (2019). Emerging technologies for 5G-enabled vehicular networks. IEEE Access, 7, 181117-181141.

Zhang, T., Tao, D., Qu, X., Zhang, X., Lin, R., and Zhang, W. (2019). The roles of initial trust and perceived risk in the public's acceptance of automated vehicles. Transportation Research Part C: Emerging Technologies, 78, 207-220. doi:https://doi.org/10.1016/j.trc.2018.11.018

Zhang, W., and Guhathakurta, S. (2017). Parking spaces in the age of shared autonomous vehicles: How much parking will we need and where? Transportation Research Record, 2651, 80–91. doi:https://doi.org/10.3141/2651-09

Appendix A

A readiness framework for effective long-range planning for CAVs classified into five categories is proposed to foster an integrated CAV environment. NCDOT and other stakeholders should plan to implement the infrastructural changes or policies and regulations based on the following criteria:

Time Horizon: This reflects the priority of the action item. Based on the results of the practitioner and industry expert survey, the time horizon is classified into three levels, (a) short-term (< 10 years), (b) medium-term (10-20 years), and (c) long-term (>20 years).

Stakeholder: This criterion represents which organization(s) should play an important role in the action item. Local and state DOTs, MPOs, RPOs, the Department of Information Technology, the Police Department, the Department of Public Works, and transit agencies are some of the stakeholders considered in this criterion.

Level of CAVs Adoption: This reflects the penetration of CAVs. In this study, three levels of CAVs adoption, (a) low, (b) medium, and (c) high, are considered. Action items detailed in the data readiness framework should be implemented based on the level of CAVs adoption. Here, "low" indicates that the requisite policies or infrastructural improvement decisions should be initiated when the level of CAVs adoption is low.

In addition to the above criteria, a general description and potential barriers to implementation are discussed. Implementing different action items reduced congestion levels and VMT, reduced travel times, increased safety levels, higher pedestrian and bicyclist safety, improved accessibility and mobility, higher equity, better reception of CAVs, and integrated and coordinated multimodal transportation system are expected.

Policy and Planning

Reposition Transportation-Related Revenues

General Description and Potential Barriers
With CAVs penetrating the transportation system, revenues are expected to decline significantly. For instance, CAVs are expected to be electric vehicles. Therefore, the revenue generated from gas taxes will reduce. Similarly, the ability of CAVs to pick up, drop off, and follow traffic rules will significantly reduce the revenue generated from parking fees, parking tickets, and violation fines. Stakeholders, therefore, need to rethink possible other sources of revenue. Possible solutions are VMT-based pricing, cordon pricing, land use, property tax, and revamping off-parking lots to higher-value areas. The potential barrier for implementing this action item is context-based, i.e., it would vary based on which solution is adopted. For instance, political and social reluctance, decisions related to pricing strategies, and equity are potential barriers to implementing VMT-based and cordon-based pricing.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

CAVs-based Land-Use Transport Demand Model

General Description and Potential Barriers
With CAVs penetrating soon, updating the existing land-use planning and transport demand models to include CAVs is essential. However, uncertainty associated with the adoption rate of CAVs would be an inherent challenge in developing CAVs, including land-use transport demand models. Stakeholders need to collect public impression data related to their willingness to (a) adopt different levels of CAVs, (b) adopt shared automated vehicles, and (c) shift to public transportation.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Promote Equitable Policies

General Description and Potential Barriers
CAVs should be operated to promote sustainable and equitable outcomes. Single-occupancy or zero-occupancy trips must be discouraged by promoting progressive and equitable road pricing. Public transportation and shared mobility options should be encouraged and incentivized. Autonomous transit and shared autonomous mobility options are ways to bridge the social inequities resulting from CAVs. Context-based public and community engagement emphasizing involving marginalized and historically underserved communities while planning for CAVs can bridge inequities.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Limit CAVs Access in Certain Spaces

General Description and Potential Barriers
Implement access limitations to create CAVs free zones. Essentially, CAVs should be restricted in high-pedestrian and bicyclist density zones to ensure non-motorized uses' safety. Local policy regulations should be formulated to restrict CAVs in pedestrian and school-zone areas. Agencies should focus on introducing geo-fencing to restrict shared CAVs, CAVs, or empty CAVs in areas with high pedestrian or cyclist densities and school zones. Political unacceptability could be one of the major barriers to the implementation of this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20-30 years, and the expected level of CAVs adoption is medium-high, i.e., the priority for implementing this action item is "medium-term."

Incentivize Public Transport and Shared Mobility

General Description and Potential Barriers
Policies promoting public transportation and shared mobility. Public Transportation can be augmented by deploying on-demand, cost-effective autonomous shuttles to enhance first-last mile connectivity. Emphasize creating a model enabling integration and prioritization of shared CAVs.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Integrated and Coordinated Multimodal Transportation

General Description and Potential Barriers
Stakeholders should emphasize integrating and coordinating multiple modes of transportation for seamless mobility. CAVs have the potential to make transportation seamless. People can park at transit stations and use automated transit systems to reach their destinations. For this, multiple modes need to be integrated. For instance, a shared autonomous service such as autonomous shuttles should be integrated with the transit system so that autonomous shuttles work as feeder services. Similarly, public bike-sharing services can be integrated as a feeder with transit systems. Integrating different modes would not only provide seamless mobility but will also improve transit ridership, accessibility, mobility, and equity, reduce VMT, congestion, and emission, and will improve safety.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Enforce Regulations on Empty Trips

General Description and Potential Barriers
Due to their potential to pick up and drop off, CAVs can increase empty or zero occupancy trips, which could lead to increased VMT and hence, congestion. Emphasis should be placed on working with different agencies to develop approaches to monitor vehicle occupancy and pricing based on occupancy. Regulations on empty trips, such that the pricing for the zero-occupant trips is higher than other occupancy trips, should be explored. VMT-based pricing should be explored to monitor zero-occupant trips. However, social and political reluctance is the major barrier to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is high, i.e., the priority for implementing this action item is "long-term."

General

Training and Education of Staff

General Description and Potential Barriers
For better reception of CAVs by the staff, stakeholders should plan to collaborate with technology providers and educational institutions to facilitate staff training. In-house training or training at institutes should be arranged. The training would ensure that staff are aware of how connectivity and automation technologies would impact transportation infrastructure and societies. Moreover, collaboration among practitioners from different departments should be promoted during the training programs. Lack of resources and expertise, work culture, funding, and rapid technological changes are potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Forming Statutory Body

General Description and Potential Barriers
An additional body that specifically deals with CAVs should be formed. The additional statutory body should be governed by dealing with the impact of CAVs and formulating policies and regulations for CAVs. The statutory body is responsible for coordinating with federal, state, and local organizations for formulating policies and strategies related to CAVs. This would avoid confusion between different organizations and would lead to standardization in CAVs related policies and legislations. Designation of CAV-specific roles, responsibilities, and tasks are potential barriers and challenges for the implementation of this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementation of this action item is "short-term."

Education and Awareness Programs for Public

General Description and Potential Barriers
PAVE POLL (2020) reported that nearly 75% of Americans perceive CAVs as not for primetime, 48% would "never get in a taxi or ride share vehicle that was being driven autonomously," and 20% of Americans feel CAVs will never be safe. Similar observations were deduced from the AAA Vehicle Technology Survey (2019). Moreover, the general public may feel unsafe and insecure on roads because of the possibility of empty or zero-occupancy trips. Therefore, to ensure a better reception of CAVs, stakeholders should plan to organize education and awareness programs for the public. This would ensure that the public is aware of CAV technology and its potential impacts. The education and awareness programs should be generated periodically.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementation of this action item is "short-term."

Vehicle Registration, Testing, Licensing, and Permits

General Description and Potential Barriers
For developing a CAVs inclusive transportation infrastructure, it is essential to identify and collect data related to vehicle type (car, SAV, bike, bus, truck, etc.), level of autonomy in each vehicle (1, 2, 3, 4, or 5), communication with infrastructure, and vehicle trips. Stakeholders should emphasize exploring vehicle registration methods that assist in identifying vehicle-level data. For instance, vehicle registration plates can be equipped with sensors containing information related to their type and vehicle identification number (VIN). The current VIN data has information related to vehicle characteristics such as make and model, features in the vehicle, and whether the feature was standard (already present in the model) or optional (flexibility to add features in the model). The sensors installed in the infrastructure can read these advanced vehicle registration plates, and comprehensive information related to the vehicle's trip can be collected. In addition to vehicle registration, stakeholders should also develop a plan for regular testing of vehicles, licensing, and issuing permits. Age limits and licensing procedures can be revisited. Data protection, privacy concerns, the potential of cyberattacks, and lack of funds are some barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Data

Standardization Of Data Collection and Reporting

General Description and Potential Barriers
Establishing standards for collecting and reporting data using a third-party platform is essential. The data related to the crash should include information related to the disengagement of autonomous features. Additional overhead costs, privacy, and data-sharing restrictions are some barriers associated with this item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Data Type

General Description and Potential Barriers
CAVs can provide detailed information regarding the vehicle over space and time. Therefore, the agencies must ponder the following questions: What kind of data should be collected? At which interval should the data be collected and stored? The answer to these questions depends on how the data will be used. If the data will be used for mobility-related and safety-related analysis, then microlevel data should be collected and stored. The level of data granularity will

govern the size of the data storage repository. In essence, micro-level data should be collected. Moreover, data from other RSUs or sensors, traffic signals and signs, and crash data should be integrated with the data obtained from CAVs to develop a comprehensive database. Data sharing and privacy concerns, lack of experience in handling big data, and lack of sufficiently large data storage facilities are potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Promote Data Sharing

General Description and Potential Barriers
Protect personal information and proprietary data and promote secure V2I enabling informing sharing. Promote security to prevent cyber-attacks. Data sharing and privacy concerns are potential barriers to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Establish Centralized Repositories, Store Data

General Description and Potential Barriers
Centralized repositories that will provide stakeholders and shareholders access to CAVs data should be established. The repositories should be partnered with trusted third parties, such as the university and the national labs, to manage data repositories. The third party should be responsible for developing transparent data storing and sharing policies. Data sharing and privacy concerns are potential barriers to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Cyber Infrastructure

Digitize Road Infrastructure

General Description and Potential Barriers
Digital road infrastructure and mapping could ensure the smooth movement of CAVs. CAVs can access these digital infrastructure repositories for route selection and optimization. Adopt LiDAR sensors to scan and assess existing road infrastructure. Periodically update the digitized road maps. Information related to work-zone, road closures, and special events should be updated on the digitized maps. Collecting detailed road inventory, streamlining the digitization process, the technology used for digitization, and overhead cost are potential barriers to implementing this action plan.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Deploy 5G Technology

General Description and Potential Barriers
As a part of the CAVs' future, the ecosystem will need to be robust, high-speed, and widely available 5G networks to support high data density arising from mobile apps, V2V, and V2I communications in real-time. Stakeholders should focus on deploying wireless 5G connectivity. Deployments can be started from city centers and then can be expanded.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10-20 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "medium-term."

Smart Intersections

General Description and Potential Barriers
Stakeholders should focus on designing and deploying smart intersections. Smart Intersections are adaptive traffic signal controls that assign red time and green time at intersections based on the traffic volume for each leg. Moreover, the focus should be on developing coordinated and adaptive traffic signal controls. The platooning capabilities of CAVs and motion planning of CAVs could increase the capacity of adaptive signals, and more benefits can be derived. Funding and uncertainty related to the adoption of CAVs are the potential barriers to the implementation.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10-20 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "medium-term."

Cloud Network and Computing Requirements

General Description and Potential Barriers
CAVs could access the digital infrastructure repository and interact with the geo-fencing grids to ensure safer movement and understand restrictions in certain land-use types. The continuous interaction will lead to congestion over the cloud, and therefore, high-end computing capabilities and larger cloud network servers would be required. Stakeholders should focus on building the cloud network and computing requirements. Data sharing and privacy concerns are potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10-20 years, and the expected level of CAVs adoption is medium to high, i.e., the priority for implementing this action item is "medium-term."

Physical Infrastructure

Prioritize Right-Of-Way for Pedestrian and Improvement in Pedestrian Infrastructure

General Description and Potential Barriers
CAVs, irrespective of the level of automation, should give right-of-way to pedestrians at crosswalks. Moreover, existing pedestrian infrastructure, such as pedestrian refuge islands, crosswalks, and signalized crosswalks, should be prioritized for improvements. Stakeholders should be involved in testing CAVs technology related to pedestrian or other object detection under varying weather conditions. This will improve pedestrian-vehicle interaction safety, resulting in fewer pedestrian crashes. Uncertain and rapid technological advancements and opposition from vehicle manufacturers are potential barriers to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "short-term."

Street Redesign

General Description and Potential Barriers
The current geometric standards may still apply for CAVs irrespective of the level of automation. Since CAVs have the potential to accurately steer, control, and track the vehicle precisely within a lane, the road can be redesigned. For example, lane widths can be reduced, automobile lanes can be narrowed in favor of non-motorized and public transportation, and road diets can be implemented. Furthermore, shoulder and emergency lanes should be maintained until the transition to ~100% CAVs. Similarly, during the transition period, emphasis should be given to maintaining the medians and barriers due to human-driven vehicles. Approval from different departments, lack of standardized guidelines for designing road infrastructure under a CAVs environment, lack of funding, and cost of redesigning are potential barriers to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 5-20 years, and the expected level of CAVs adoption is low/medium, i.e., the priority for implementing this action item is "short/medium-term."

Separated/Protected Bike Lanes

General Description and Potential Barriers
Stakeholders should focus on designing and implementing separated/protected bike lanes and effectively managing curb space. This will separate bicycles from vehicular traffic, improving bicycle rider safety. Street redesigning should be prioritized for pedestrians, bicyclists, and transit riders. If separate bike lanes cannot be provided, then temporary or flexible lanes for cycling are provided. The temporary bike lanes can be installed using movable barriers. Funds for designing and implementing protected bike lanes are one of the major barriers influencing the implementation of this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 15 years, and the expected level of CAVs adoption is low, i.e., the priority for implementing this action item is "medium-term."

Update Road markings

General Description and Potential Barriers
Stakeholders should focus on updating road makings as CAVs need clear marking to function properly. Improper delineation of road markings poses challenges for vision sensors of CAVs to predict the vehicle's position in the lane. Human drivers and CAVs' machine-vision systems should read the road marking. An increase in the thickness or width of the road marking is proposed. In addition to improving road marking, the focus should also be placed on employing new technology, such as applying magnetic material or sensors embedded in the pavement to improve the positioning and navigation of CAVs. Lack of funding, uncertainty of adoption rates, and lack of design guidelines are the potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "short-term."

Update Traffic Signs

General Description and Potential Barriers
CAVs, like human drivers, need to detect, read, and understand traffic rules to navigate safely. The current technology of CAVs is based on computer vision that records and interprets the color of traffic signs based on their color, shape, and message. Road signs, such as variable message signs, are difficult to read with computer vision technology. Rural areas may pose significant challenges compared to urban areas primarily because of a lack of infrastructure. In that, low-cost technology based on "QR codes" can be implemented. However, QR code technology would be complex for humans to read and interpret. With CAVs able to communicate with infrastructure, this technology can be leveraged further by installing sensors on traffic signs. The sensor can communicate with CAVs to ensure safe movement. Lack of funds, lack of standardized traffic sign design guidelines, lack of comprehensive operation and maintenance schedule, and lack of funding and experts are potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "short-term."

Update Traffic Signals and Intersections

General Description and Potential Barriers
Literature suggests that CAVs contribute to an increase in the efficiency of traffic flow at intersections by increasing capacity and reducing waiting time at the intersection. Therefore, to leverage this benefit, stakeholders should emphasize updating traffic signals and intersections with sensors that can effectively communicate with CAVs using wireless technology to ensure

smoother and safer travel. In addition to updating traffic signals and intersections, 5G wireless technology and digitized road infrastructure should be simultaneously planned.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "short-term."

Pavement Surface Condition

General Description and Potential Barriers
CAVs are likely to have precise steering control, and therefore, the vehicle would be maintained in the center of the lane via LC or LKA. There is a need to investigate the effect of CAVs on pavement deterioration and establish a trade-off between speed limit, number of lanes, and pavement deterioration. Research on how pavement friction will influence the performance of CAVs in terms of rear-end and lane-change crashes will be helpful. Although CAVs can interact with other vehicles via V2V and V2I communications, the probability of hard barking will reduce. Lack of pilot testing and funds are potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20-30 years, and the expected level of CAVs adoption is high, i.e., the priority for implementing this action item is "long-term."

Improve Lighting

General Description and Potential Barriers
Adequate illumination, especially on urban roads, is essential during night hours to ensure road safety for all users. There is a need to improve lighting facilities, i.e., illuminance and spacing. Street lighting will also improve the performance of CAVs, particularly under adverse weather conditions.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium to high, i.e., the priority for implementing this action item is "medium-term."

Modify/Adapt Speed Limit

General Description and Potential Barriers
Speed is one of the risk factors influencing the severity of crashes. Through the information obtained through wireless communication between the onboard and roadside sensors, CAVs are expected to comply with the speed limits, and therefore, the proportion of crashes resulting from human errors and overspeeding will be reduced significantly. World Bank Report (2021) proposes a maximum speed limit of 20mph in urban areas to significantly lower the risk and severity of crashes. Variable speed limits could be one of the potential strategies agencies can think of to improve efficiency and safety. However, the current infrastructure and vehicle technology are not ready to support variable speed limits. Continuous changes in speed limit may be difficult for the computer vision technology of the CAVs to read and interpret. Stakeholders should focus on modifying or adopting lower speed limits to ensure smooth and safer operations in the CAVs environment. In addition, emphasis should be placed on digitizing

existing road infrastructure and deploying sensors on speed limit signs for effective communication. Social unacceptability could be a potential barrier to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 15-20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Add Vehicle Charging Stations

General Description and Potential Barriers
CAVs are expected to be electric vehicles; therefore, the agencies should focus on adding vehicle charging stations around the region and in hotspot locations. The charging stations also bring other associated challenges, such as parking spots to provide electric charging options. Stakeholders should explore updating infrastructure with charging abilities rather than charging stations. Ensuring equity in addition to vehicle charging stations, lack of funds, and low utilization in the early periods are potential barriers to implementing this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20-30 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "long-term."

Demarcate Clear Pick-Up and Drop-Off Zones

General Description and Potential Barriers
CAVs have the potential to pick up and drop off, and therefore, stakeholders should focus on demarcating and establishing clear pick-up and drop-off zones. The decision where these pick-up and drop-off spots should be placed must be taken, considering traffic safety and efficiency. Retrofitting existing roads and the requirement of new building codes are some of the potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Rethink Parking Requirements

General Description and Potential Barriers
Considering that CAVs have the potential to pick up and drop off, off-street and on-street parking requirements for different land-use types should be revisited. For instance, on-street parking lanes can be reclaimed to manage traffic. Social backlash due to the lack of parking facilities is the most significant barrier to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 20 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "medium-term."

Operation and Maintenance

General Description and Potential Barriers
For developing a CAVs inclusive infrastructure and environment and ensuring that CAVs function safely, many infrastructure changes, such as upgradation in traffic signs, signals, intersections, markings, additions of charging stations, and demarcations of clear pick-up and drop-off zones, are needed. Moreover, wireless connectivity, sensors, and other roadside units will be installed at many locations. Physical and cyber-physical infrastructure elements must be periodically maintained to ensure CAVs operate safely. Adopt LiDAR sensors to scan and assess existing road infrastructure. Moreover, employ artificial intelligence-based video analytics to assess existing infrastructure. Stakeholders should emphasize developing a periodic operation and maintenance schedule. Roles and responsibilities should be designated appropriately to ensure the timely maintenance of different infrastructure-related elements. Lack of robust operation and maintenance schedule and lack of updated road inventory database are the potential barriers to this action item.

Time-Horizon and Level of CAVs Adoption
Stakeholders should be ready with the implementation plan within the next 10 years, and the expected level of CAVs adoption is medium, i.e., the priority for implementing this action item is "short-term."