NCHRP 20-102(19)
Update AASHTO's Connected Vehicle/ Automated Vehicle Research Roadmap

Task 1 Report

Commentary on Current Research Roadmap and Completed Projects

Prepared for

National Cooperative Highway Research Program (NCHRP)

Transportation Research Board of

The National Academies of Sciences, Engineering, and Medicine

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DISCLAIMER

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INTRODUCTION

Connected and Automated Vehicle technologies are fast advancing and are expected to transform the transportation landscape. It is expected that they can improve roadway safety, reduce congestion and its associated costs, and improve land use and the environment. While Connected Vehicles (CVs) and Automated Vehicles (AVs) are two separate categories of vehicles, several studies indicate that convergence of these technologies, leading to Connected and Automated Vehicles (CAVs), could potentially gather benefits of both and lead to a more safe and efficient transportation system.

The U.S. Department of Transportation (USDOT), industry, and research institutes have led a wide range of research and development (R&D) activities that focused on enhancements in communications and vehicle technologies. These activities led to the development of several CV applications that have already moved from research to deployment phases. The expected benefits of these technologies have led some state and local departments of transportation (e.g., Arizona, California, Florida, Michigan, Minnesota, New York, Virginia) to engage in prototyping, testing, and evaluating CV technologies. Several states and metropolitan areas are pursuing the USDOT-sponsored CV Pilots and leveraging the lessons learned to enhance their own CV implementations [1].

In addition, automobile manufacturers and suppliers and large technology firms (such as Google and Apple) are advancing Automated Vehicle technologies that progressively reduce dependence on drivers. The Society of Automotive Engineers define levels of automation (levels 1 through 5) based on the driving load distribution between the driver and the vehicle. As the level of automation in the marketplace evolves from current SAE Level 2 to Level 4, and the synergies between AVs and CVs become more obvious, future vehicles are expected to fully monitor the road conditions and perform much of the safety-critical driving functions, leading to significant improvements in safety and efficiency [2].

Moreover, the sharing economy has influenced numerous sectors of the economy including: finance, logistics, last-mile delivery, hospitality, and transportation. Technological, mobility, and social trends are also changing the way people travel and consume resources. These trends have contributed to the rise of innovative transportation services, such as shared and on-demand mobility [3].

The emergence of safer, more efficient CAVs will fundamentally change the way federal, state, and local agencies will plan, operate, maintain, and regulate the transportation system and impact future transportation infrastructure investments. These agencies must understand both the impact of CAV technologies on the systems they manage, as well as the effects of their policy, planning, and regulation; infrastructure design; and operations on technology development, adoption, and life-cycle costs. In addition, fundamental changes in the relationships among mobility providers, consumers, technology and service providers, and public agencies may necessitate public-private collaboration to fully capitalize on the opportunities presented by automation [4].

Thus, a coordinated research program that can anticipate and address the needs of state and local transportation agencies and supporting organizations, such as the American Association of State Highway and Transportation Officials (AASHTO), in this changing landscape is critical. A broad range of issues that must be addressed include:

- Standardization (e.g., roadside signs, technologies, etc.);
- The impacts of regulation on innovation;
- Reduced infrastructure life cycles (in the context of information technologies);
- Safety and liability;
- Cybersecurity;

- Privacy protection;
- Impacts on public agency workforce
- Data sharing, standards, access, and management; and
- New forms of vehicle ownership and access.

Consequently, the National Cooperative Highway Research Program (NCHRP) initiated the program 20-102 to assess the impacts of CVs and AVs on state and local transportation agencies. The program's objectives are to: (1) identify critical issues associated with CAVs that state and local transportation agencies and AASHTO will face, (2) conduct research to address those issues, and (3) conduct related technology transfer and information exchange activities [5]. To help the NCHRP 20-102 program facilitate research in these topic areas, a draft research roadmap was developed in 2015 as part of the NCHRP 20-24 project that identified a list of projects under four general clusters – (a) Institutional and policy, (b) Infrastructure design and operations, (c) Planning, and (d) Modal applications [4]. Consequently, several research projects and task orders were initiated by NCHRP to cover the plethora of topics identified in the roadmap. Due to the fast-changing nature of this topic, NCHRP also identified recurring updates to the roadmap and related lists of research areas to keep up with the changing research needs.

1.1 Project Objective

The objective of this project, NCHRP 20-102(19) - Update AASHTO's Connected and Automated Vehicle Research Roadmap, is to update the 2015 roadmap and to identify priority research areas to focus [6]. To support this objective, we are undertaking three distinct tasks, as shown in Figure 1.

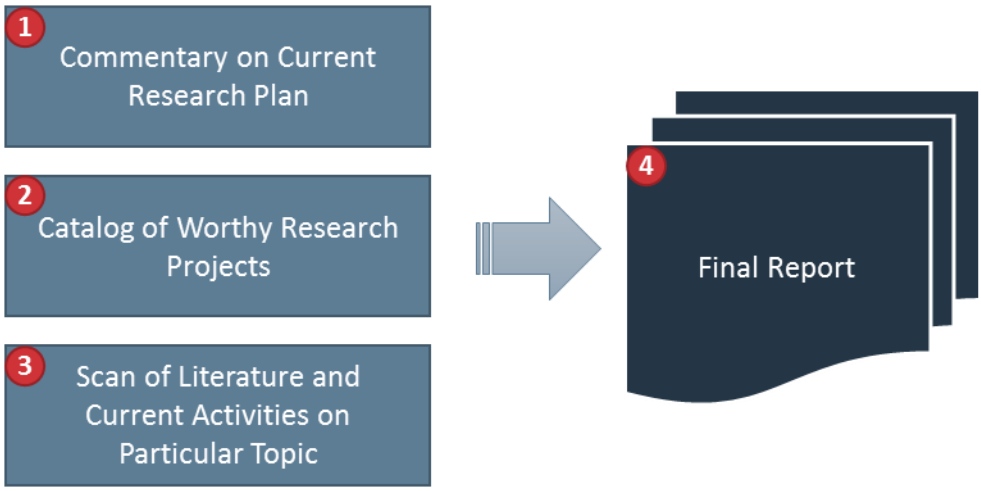

Figure 1. Tasks performed under NCHRP 20-102(19) Task Order

The first step is to develop a commentary on the current research plan and the research completed to date. The commentary not only includes major findings from existing research but also an analysis of the gaps in research from the original vision and how the findings map to the current state-of-the-art. This analysis is anticipated to feed into the next step to develop a catalog of worthy research projects. The project team will do this by creating a "living" catalog that not only lists the broad topic areas that need to be researched but also defined research objectives under each of the topic areas. Lastly, the project team will also develop a series of white papers on selected topics of importance that can help NCHRP to draft problem statements for funding future research.

1.2 Report Overview

This report presents the first step of this project, commentary on the current research plan and completed research. This report is divided into five chapters:

1. **Introduction:** This chapter introduces the project and task objectives.
2. **Summary of Previous Roadmap:** This chapter provides a summary of the previous roadmap that was developed in 2015 to provide a precedence to the following chapters.
3. **Commentary on Completed Projects:** This chapter provides a summary of the different projects that were undertaken by NCHRP regarding CVs/AVs and a commentary on each of the completed ones.
4. **Issues and Gaps:** This chapter addresses issues with the previous roadmap and any potential gaps in the initial research topics, such as inconclusive data or more specific topics to explore.
5. **Next Steps:** This chapter discusses next steps for the project team using the findings from this report.

2. SUMMARY OF PREVIOUS ROADMAP

In this chapter, we summarize the previous research roadmap that was developed in the context of CVs/AVs for AASHTO. Developed in 2015 as part of the NCHRP 20-24(98) project, the roadmap addressed policy, planning, and implementation issues that state and local transportation agencies would face during CV and AV deployment and considered the implications of connected automated vehicle (CAV) technologies for various roadway users (e.g., passenger cars, trucks, public transit vehicles, emergency vehicles, bicycles, pedestrians), as well as agency fleets [4].

The roadmap consisted of a catalog of institutional, legal, policy, and operational issues related to CAV technologies that will affect agencies and the public prioritizing critical near-term issues for research by consolidating rankings by the panel. These highest-ranked issues were consolidated into projects, with a description of goals, scope, anticipated outcomes, budget, schedule, and linkages to associated research and efforts undertaken by others. To this end, 23 projects were identified for near-term research that fell into four categories as described below. The following sections provide descriptive project titles and desired outcomes from each of these projects.

2.1 Institutional and Policy Topics:

Seven topics were identified in the area of institutional and policy issues, as shown in Table 1.

Table 1. Institutional and Policy topics identified in NCHRP 20-24(98)

Sl. No.	Project Title	Desired Outcome
1.1	Implications of automation for motor vehicle codes	Recommendations for changes to laws and regulation of motor vehicle codes to address AV technologies
1.2	Business models for CV/AV infrastructure deployment	Guidelines for investment decisions based on public and private benefits
1.3	Public agency actions to facilitate CV/AV implementation	Recommendations for policy actions with impact assessments of each
1.4	Harmonization of state regulations	Compendium of regulatory issues and action plan for resolution
1.5	Federal-state-local boundaries of responsibility	Recommendations for actions to resolve ambiguities
1.6	Lessons learned from other transportation technology roll outs	Recommendations for how to improve upon past lessons learned
1.7	Lessons learned from CV pilot deployments	Consolidated lessons from CV pilots to inform other agencies

2.2 Infrastructure Design and Operations

Ten topics were identified in the area of infrastructure design and operations, as shown in Table 2 below.

Table 2. Infrastructure Design and Operations topics identified in NCHRP 20-24(98)

Sl. No.	Project Title	Desired Outcome
2.1	Roadway infrastructure design	Recommendations for infrastructure elements to improve AV performance

2.2	Tools for predicting AV/CV impacts	Models for use in prospective assessment of AV/CV deployment systems
2.3	CV/AV applications for maintenance fleets	Agency recommendations for bundling of apps relevant to maintenance fleets
2.4	Relationships of connected and automated vehicle systems	Report on how CV data can support AV operation
2.5	Traffic control strategies with consideration of AVs	Concepts for revamping or enhancing traffic control strategies with AV systems
2.6	Dedicated lanes for CV/AV operation	Report assessing how dedicated lanes could be used to accelerate CAV benefits and deployment
2.7	Geometric design concepts for AV systems	Recommendations for roadway design modifications facilitating AV
2.8	Cybersecurity implications of CV/AV on state and local operating agencies	Primer on cybersecurity issues and needed agency actions
2.9	Workforce capability strategies for state and local agencies	State of the practice summary and recommendations for future staffing
2.10	Data management strategies for CV/AV applications	Recommendations for agency actions to manage and maintain incoming and outgoing data

2.3 Planning Issues

Three topics were identified in the area of planning issues as shown in Table 3 below.

Table 3. Topics associated with Planning Issues identified in NCHRP 20-24(98)

Sl. No.	Project Title	Desired Outcome
3.1	Including consideration of AV systems in the regional planning process	Algorithms and tools for modifying planning models; sample case study results
3.2	Assessing transportation system impacts of CV/AV	Predictions of BCA impacts of CV/AV technology in various environments
3.3	Effects of AV/CV on land use, travel demand, and traffic impact models	Algorithms, data and tools for modifying long-term land use and travel demand models; sample results

2.4 Modal Applications

Three topics were identified in the area of modal applications as shown in Table 4 below.

Table 4. Topics associated with Modal Applications identified in NCHRP 20-24(98)

Sl. No.	Project Title	Desired Outcome
4.1	Impacts of public transit system regulations and policies on AV/CV technology introduction	Recommendations for changes to regulations to encourage innovation
4.2	AV/CV applications for long-haul freight operations	Recommendations and plan of action to address challenges
4.3	BCA of AV public transit systems	Analysis of AV public transit scenarios and comparative assessment with traditional transit systems

In the next chapter, we discuss how this research roadmap has been implemented in terms of executed projects.

3. COMMENTARY ON COMPLETED PROJECTS

In this chapter, we provide a commentary on the completed projects that were performed either under the NCHRP 20-102 umbrella of projects [5] or other programs such as NCHRP 20-24 and other cooperative research programs.

3.1 List of 20-102 Projects

As shown in Table 5, 19 problem statements were developed as part of the NCHRP 20-102 program. While several of them map directly to the previous AASHTO Research Roadmap, the problem statements also include additional projects of interest to AASHTO and NCHRP panel members, such as minimum safety data needed for AV-related crash analysis, etc. Some projects were also combined with other related problem statements as shown below. As of May 2018, five projects were completed, and six projects were on-going.

Table 5. NCHRP 20-102 projects that are completed, on-going and pending award.

Project Number	Title	Status
NCHRP 20-102(1)	Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems into Market Decisions [7]	Completed
NCHRP 20-102(2)	Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations [8]	Completed
NCHRP 20-102(3)	Challenges to CV and AV Application in Truck Freight Operations [9]	Completed
NCHRP 20-102(4) + NCHRP 08-116	Framework for Managing Data from Emerging Transportation Technologies to Support Decision-Making [10]	Not started
NCHRP 20-102(5)	Strategic Communications Plan for NCHRP Project 20-102 [11]	Not started
NCHRP 20-102(6)	Road Markings for Machine Vision [12]	On-going
NCHRP 20-102(7)	Implications of Automation for Motor Vehicle Codes [13]	Completed
NCHRP 20-102(8)	Dedicating Lanes for Priority or Exclusive Use by CVs and AVs [14]	Completed
NCHRP 20-102(9)	Providing Support to the Introduction of CV/AV Impacts into Regional Transportation Planning and Modeling Tools [15]	On-going
NCHRP 20-102(10) + NCHRP 03-127	Cybersecurity Implications of CV/AV Technologies on State and Local Transportation Agencies [16]	On-going
NCHRP 20-102(11)	Mobility-on-Demand and Automated Driving Systems: A Framework for Public-Sector Assessment [17]	On-going
NCHRP 20-102(12)	Business Models to Facilitate Deployment of CV Infrastructure to Support AV Operations [18]	On-going
NCHRP 20-102(13)	Planning Data Needs and Collection Techniques for CV/AV Applications [19]	Not started
NCHRP 20-102(14)	Data Management Strategies for CV/AV Applications for Operations [20]	Not started

NCHRP 20-102(15)	Impacts of Connected and Automated Vehicle Technologies on the Highway Infrastructure [21]	Not started
NCHRP 20-102(16)	Preparing Traffic Incident Management (TIM) Responders for Connected Vehicles and Automated Vehicles [22]	Not started
NCHRP 20-102(17)	Deployment Guidance for CV Applications in the Open Source Application Development Portal [23]	Not started
NCHRP 20-102(18)	Minimum Safety Data Needed for Automated Vehicle Operations and Crash Analysis [24]	Not started
NCHRP 20-102(19)	Update AASHTO's Connected Vehicle/Automated Vehicle Research Roadmap [6]	On-going

3.2 List of Other Projects

Several problem statements were also developed outside of the NCHRP 20-102 umbrella on related topics for funding and execution, some of which are shown in Table 6 below.

Table 6. Other TRB projects in the associated topic areas.

Project Number	Title	Status
ACRP 11-03 (S03-11)	Transportation Network Companies: Challenges and Opportunities for Airport Operators [25]	Completed
ACRP 03-48	Advanced Ground Vehicle Technologies (AGVT) for Airside Operations [26]	Not started
TCRP J-05 (18-03)	Workplace Implications of Autonomous Vehicles on the Transit Workforce [27]	Not started
TCRP J-11 (21)	The Impact of New Technology-Enabled Mobility Services on Public Transportation [28]	Completed
TCRP J-11 (26)	Collaborations and Partnerships between Public Transportation and Transportation Network Companies (TNCs) [29]	Not started
TCRP J-11 (27)	Analysis of Low-Speed Automated Vehicle (LSAV): Pilots and Deployments [30]	Not started
NCHRP 20-24(111)	State CEO Leadership Forum on Connected & Autonomous Vehicles and Transportation Infrastructure Readiness [31]	Completed
NCHRP 20-24(112)	Connected Road Classification System (CRCS) Development [32]	On-going
NCHRP 03-127 + NCHRP 20-102(10)	Cybersecurity of Traffic Management Systems [33]	On-going
NCHRP 08-116 + NCHRP 20-102(4)	Framework for Managing Data from Emerging Transportation Technologies to Support Decision-Making [10]	Not started
NCHRP 08-117	Impact of Transformational Technologies on Land Use and Transportation [34]	Not started

3.3 Review of Completed Projects

In this section, we provide a summary of completed and nearly completed projects to help identify any gaps from the original problem statement or vision.

3.3.1 Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems into Market Decisions

This project was focused on identifying and describing policy and planning actions at the state, regional, and local levels that could help societal impacts (including impacts on the transportation system owner/ operators) of CV/AV technologies to be internalized in market decisions made by individuals and organizations. This project was completed in May 2017 by Texas A&M Transportation Institute for a budget of $400,000 [7].

This project resulted in three deliverables: (a) briefing document intended for state, regional, and local agency and political decision-makers who are developing public policy for these transformational technologies, (b) full report, and (c) video developed by AASHTO to introduce the briefing document and full report [7].

At a high level, this research [35] found that society could benefit if state, regional, and local governments implemented policy and planning strategies to: (a) internalize these externalities in decision making by consumers and (b) reduce negative societal effects and increase positive societal effects of AVs and CVs, regardless of whether they are internal or external to market decisions. In this context, it provides 18 policy strategies to help facilitate the following outcomes to:

1. Mitigate Safety Risks through Testing, Training, and Public Education
2. Encourage Shared AV (SAV) Use
3. Address Liability Issues that May Impact Market Development
4. Enhance Safety, Congestion, and Air Quality Benefits by Influencing Market Demand.

In addition to providing these policy strategies, the research team also provided topics that need to be examined, including, but not limited to return on investments (ROI) on CV/AV investments, future public transportation scenarios for planning agencies, public-private partnerships in monetizing CV/AV data, the financial impact of AVs, and others.

3.3.2 Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations

This project sought to document the current regulatory and policy landscape of public transit system planning, development, funding, implementation, and operations that could impact the introduction of CV/AV technologies, as well as the regulatory and policy changes that may be needed to facilitate the enhancement of existing and new forms of public transportation enabled by various CV/AV technologies. The project was completed in May 2017 by Kimley Horn for a budget of $150,000 [8].

This project resulted in a full report [36], which includes five topic areas that form the breadth and depth of the findings:

1. Automated Vehicle Technology and Deployment Scenarios for Public Transit
2. Safety Assurance Considerations – Blending Transit and Automotive Safety Analysis Methodologies
3. Workforce Deployment – Changes and Provisions of Future Policy and Contracts

4. Operating Agency Policy – Potential Issues and Changes Required
5. Government Laws and Regulations – Issues and Changes to be Considered.

In addition to documenting the state-of-the-practice and potential future directions in the context of using CVs and AVs in public transit, the report also identifies nearly 30 different potential research activities in this area organized into five categories.

3.3.3 Challenges to CV and AV Application in Truck Freight Operations

Focused on heavy truck movement, the report identifies existing and emerging freight regulatory, planning, policy, and operational environments and challenges for CV/AV truck technologies. The report examines barriers and opportunities that the public and private sector may face when implementing these technologies in freight operations. In addition, the report explores next steps for addressing the challenges for deployment and adoption. This project was completed in January 2017 by Booz Allen for a budget of $150,000 [9].

This project resulted in a full report [38] that summarizes the state-of-the-practice and other on-going research in the area of CV/AVs for freight operations. Specifically, the findings are classified into six categories: (a) Technology; (b) Application Scenarios; (c) Legal, Regulatory, and Policy Topics; (d) Freight Planning Topics; (e) Stakeholder Engagement; and (f) Deployment. In addition, the project team also identified research needs in terms of planning, establishing a regulatory environment (including laws, policy and regulation, and enforcement), CV/AV applications research and testing, and developing technical standards and the outreach and communication required in supporting deployment.

3.3.4 Implications of Automation for Motor Vehicle Codes

Existing motor vehicle codes have been developed based on implicit assumptions about drivers maintaining continuous involvement in the driving task and managing traffic safety hazards. Automated driving systems significantly reduce the role of the driver, which means that some of these codes will need to be reconsidered. The incorporation of driving behavior into in-vehicle software also generates pressure to harmonize the rules of the road across jurisdictions. The objective of this project was to provide state departments of transportation (DOTs) and motor vehicle departments with guidance and resources to assist with the legal changes that will result from the roll out of CAVs. This project was completed in February 2018 by VTTI for a budget of $350,000 [13].

This project resulted in a full report [not yet published] aimed at a legal and regulatory prioritization assessment and harmonization analysis for CAVs. While the project considered a number of assumptions in the analysis, it provided a list of legislative and regulatory changes to bolster CV and AV adoption. The project team concluded that the period 2018–2020 is an important timeframe for states to begin legislation and regulation changes. States can choose to make these modifications earlier, but they should also closely monitor the marketplace and any federal oversight direction. Just as importantly, any modifications suggested should be in a form that allows for flexible updating and ease of adaptation.

3.3.5 Dedicating Lanes for Priority or Exclusive Use by CVs and AVs

CV and AV systems have been shown to work more effectively and provide much higher lane capacity when equipped vehicles are clustered in close proximity to each other in the same lane. Hence, dedicating lanes to CVs and AVs for priority or exclusive use could catalyze market penetration of these technologies. Consequently, one of the research projects aimed at developing guidance on the conditions that may be amenable to dedicating lanes for CAV users and documenting the specific policy actions that are needed

to make this feasible [14]. This project was completed in April 2018 by Booz Allen for a budget of $350,000, and a final report was developed.

The project: (a) identified categories of benefits and disbenefits to users of dedicated lanes and general purpose lanes, as well as to the owners and operators of dedicated lane facilities under different conditions; (b) assessed the state-of-the-research with respect to CV/AV applications and algorithms that can be used when dedicating freeway lanes; (c) modeled CV/AV applications in two different case study sites; and (d) used these models to conduct sensitivity analysis of factors that contribute to different mobility, safety and environmental performance measures under different dedicated lane scenarios. Based on this research, the project team developed specific guidance for agencies interested in converting lanes to dedicated CV/AV lanes. The project team also documented specific laws and regulations that might impact dedicating lanes to specific user categories. The project report [not yet published] also identified limitations of this research and potential future research topics, such as researching more CV/AV applications in light of dedicated lanes and expanding research to dedicated arterial lanes.

3.3.6 Road Markings for Machine Vision

The objective of the research was to develop information on the performance characteristics of pavement markings that affect the ability of Machine Vision (MV) systems to recognize them. The study was focused on center lines, no-passing zone markings, lane lines, and edge lines as defined by the Manual on Uniform Traffic Control Devices (MUTCD). Factors considered included pavement marking presence; type of marking (flush, raised, recessed, or temporary); contrast between the pavement and the marking during daytime and nighttime conditions; different weather conditions (rain, fog, etc.); pavement uniformity (including sealed cracks and patching); vehicle speed; and the impact of other substances on the road, such as snow, sand, salt, and water.

The ongoing study by Texas Transportation Institute for $200,000 will end in May 2018 [12], and it will result in a final report. The results of this study [report not yet published] suggest that the contrast ratio of the longitudinal pavement markings relative to the pavement should be around three, meaning that a marking luminance factor or coefficient of retroreflected luminance should be three times higher on the pavement marking than on the adjacent pavement surface. In addition, broken markings should use higher-contrast material than comparable continuous markings due to the reduced marking signal resulting from the intermittent nature of the markings. Along the same lines, the usage of raised pavement markers as longitudinal delineation in the absence of standard pavement markings may not be sufficient for adequate MV detection. Finally, where insufficient contrast can be achieved by the combination of marking and pavement alone, bordered contrast pavement markings can be used to improve MV performance.

The research team also acknowledged the limitations of this study and provided future research directions that include expanding the type of MV systems studied, expanding the testable Operational Design Domain (ODD) scenarios, different types of pavements, as well as different speed limits.

3.3.7 Summary of Other TRB Cooperative Research Program Projects.

In addition to the projects completed or nearing completion under the 20-102 umbrella, the project team also reviewed specific projects under NCHRP, Airport Cooperative Research Program (ACRP), and the Transit Cooperative Research Program (TCRP) on emerging transportation technologies and applications that may have been indirectly impacted by the previous research roadmap. These projects, highlighted in Table 6, highlight impacts of emerging mobility services, such as ridesourcing/TNCs, or operational

changes in implementation as well as new challenges, such as public acceptance of these technologies including the workforce. A quick summary of these are provided below:

- ACRP 11-03: Transportation Network Companies: Challenges and Opportunities for Airport Operators – This project completed in August 2017 and developed a synthesis of: (a) how airport operators regulate TNCs including: enforcement, assignment of curb space, monitoring trips, etc. and (b) revenue generation for airports from TNCs and vice versa [38].
- TCRP J-11(21): The Impact of New Technology-Enabled Mobility Services on Public Transportation – This project completed in May 2016 examined the relationship of public transportation (including paratransit and demand-responsive services) to shared modes including: bikesharing, carsharing, microtransit, and ridesourcing/TNC services provided by companies, such as Uber and Lyft [39].
- NCHRP 20-24(111): State CEO Leadership Forum on Connected & Autonomous Vehicles and Transportation Infrastructure Readiness – This project aimed at bringing together state CEO leadership to discuss CV/AV readiness during a peer-exchange conducted during the ITS World Congress 2017. The discussions centered around three themes: (a) taking more initiative, (b) developing stronger capabilities and resources, and (c) being a more effective partner [31].
- NCHRP 20-24(112): Connected Road Classification System (CRCS) Development – This on-going project, expected to be completed in August 2018, aims at developing a consensus CRCS that will be useful to state and local departments of transportation and metropolitan planning organizations that are planning or implementing CV- and AV-compatible infrastructure and is building on Colorado's RoadX classification that categorizes roadways to six levels of infrastructure readiness based on the complexity and level of automation [32].
- NCHRP 03-127/NCHRP 20-102(10): Cybersecurity of Traffic Management Systems – This on-going project, expected to be completed in August 2019, aims at developing guidance for state and local transportation agencies on mitigating the risks from cyber-attacks on the field side of traffic management systems (including traffic signal systems, intelligent transportation systems, vehicle-to-infrastructure systems (V2I), and closed-circuit television systems) and, secondarily, on informing the agency's response to an attack [33].

4. GAPS IN RESEARCH IMPLEMENTATION

Chapter 2 summarized the current research roadmap, and Chapter 3 expanded on the implementation status in terms of projects that are completed, on-going, and planned. As listed in the previous chapter, several projects for which an active problem statement was developed were completed or nearing completion. However, several projects that were identified in the previous AASHTO roadmap were also not developed into a problem statement. They were:

1. Harmonization of state regulations
2. Federal-state-local boundaries of responsibility
3. Lessons learned from other transportation technology roll outs
4. Tools for predicting AV/CV impacts
5. CV/AV applications for maintenance fleets
6. Relationships of Connected and Automated vehicle systems
7. Traffic control strategies with consideration of AV
8. Geometric design concepts for AV systems
9. Workforce capability strategies for state and local agencies (partially covered under NCHRP 20-102(16))
10. Benefit-Cost Analysis of AV transit systems (partially covered under certain TCRP J-11 Task Orders)

While the current roadmap provided a great baseline and a guideline for initiating several critical projects under NCHRP 20-102 [5], new factors and constraints will define the gaps in research implementation.

4.1 Changes Since Last Roadmap

CV/AV is a very dynamic topic, and as such the research needs are evolving. The previous roadmap [4] developed in 2015 was reflective of the state-of-the-practice at that time and needs to be updated is based on several factors. This section summarizes these factors.

1. USDOT has released two iterations of its Federal Automated Vehicle Policy and is planning to release a third iteration during 2018, providing more clarity about the roles that the federal government intends to play in the advancement of CAV technology and applications [40].
2. While the USDOT has invested several years on CV-focused research, more recent projects have been more AV-focused to reflect the needs of the fast-evolving space. We cannot accurately predict the entire scope of the future USDOT research landscape, only that it will evolve in real-time much as the NCHRP 20-102 roadmap has evolved in real-time.
3. There is a greater emphasis on data-related themes with the expansion of data availability, collection, sharing, aggregation, and re-dissemination through crowd-sourced, private, and public-sector sources facilitated through Application Program Interfaces (APIs) and other third-party tools. USDOT even identified near-term data exchange priorities for the industry to enable and bolster safe roll out of CAVs, such as monitoring planned/unplanned work-zones, providing real-time road conditions information, diversifying CAV testing scenarios, improving cybersecurity of CAVs, and improving roadway inventory databases, etc. [41].
4. Shared economy research areas, including shared mobility and mobility-on-demand are increasingly impacting transportation systems operations and planning, travel demand modeling, and even revenue-driving business models.
5. Congress is debating bills that could establish a number of policy and regulatory actions if enacted. The implications of these policies at the state and local levels should be studied once/if the bills become law.

6. SAE J3016 taxonomy and definitions for Automated Driving Systems have become internationally standardized as the basis for regulatory considerations and technical discussions about road vehicle automation [42]. Because the concepts are complicated and subtle, it is challenging to express them in ways that are easy for non-specialists and the general public to understand.
7. SAE J3613 is developing a taxonomy and definitions for terms related to shared mobility and enabling technologies.
8. The state-of-the-industry with respect to automation is more advanced in all modes, including automated truck platooning, automated trains, low-speed automated shuttles, automated personal vehicles (higher-levels of automation becoming market ready), etc.
9. There has been growing recognition throughout the industry on the importance of issues, such as ethics, personal privacy protection, and cybersecurity for the implementation of road vehicle automation systems. Additionally, researchers are exploring ways to develop XAI (explainable artificial intelligence) methods that could be basis for automated driving systems.
10. Several states have implemented regulatory frameworks to govern the testing and public operation of Highly Automated Vehicles (HAV). This includes changing definitions of "driver" to include "driving systems," potential ways to conduct inspection of such systems, as well as research in the area of updates to the Federal Motor Vehicle Safety Standards (FMVSS) [43].
11. The diversity of road vehicle automation operational concepts has become much better understood, with a broader recognition that there will be a wide variety of narrowly specialized automation systems before it will become feasible to implement automation systems that will take over the majority of human driving roles.
12. Infrastructure owners and operators have taken an increasingly active role in supporting CAV testing on their facilities, engaging in CV pilot deployments, and considering CAV impacts on both short- and long-term planning exercises and modeling, as well as on operations and maintenance of new devices.
13. Impact of issues such as adverse weather, human factors, and under-developed infrastructure on the operation of highly automated vehicles are becoming more apparent due to increased HAV testing on open roads.

4.2 Current Roadmap Topics Not Executed or Planned

In this section, we highlight the topics from the current roadmap that were executed and planned to be executed, including a commentary on whether the research need is still valid.

Table 7. Listing of research needs that were not funded.

Sl. No.	Title	Still Valid?	Comments
1.4	Harmonization of state regulations	Yes	While some of the aspects of this research was undertaken as part of NCHRP 20-102(7) on *Implications of Motor Vehicle Codes,* this research requires ongoing updates based on changes in the state and federal regulatory and legislative policies. As the USDOT releases updates to its original guidance, and federal legislation possibly takes shape, the state regulatory processes need to be reviewed to determine the extent to which harmonization is achievable.
1.5	Federal-state-local boundaries of responsibility	Yes	This research need is still valid, and it could be tied to another research need that assesses the CV/AV deployment scenarios.

Sl. No.	Title	Still Valid?	Comments
1.6	Lessons learned from other transportation technology roll outs	Yes	There are lessons to be learned from CV pilot implementations, smart cities, AV pilot programs conducted by state and local agencies, Mobility-on-Demand (MOD) Sandbox demonstrations, etc.
1.7	Lessons learned from CV Pilot Deployments	Yes	There are multiple projects aiming at documenting the lessons learned from CV pilot deployments. For example, NCHRP 20-102(17) aims at looking into developing deployment guidance for CV applications on OSADP. In addition, a review of lessons learned from the "data management" piece of CV Pilots is included in other projects, such as NCHRP 08-116. There are also numerous non-USDOT sponsored projects aiming at deployment of Connected Vehicle applications in response to the National SPaT Challenge. Consequently, there may be value to consolidating lessons learned from all these deployments.
2.2	Tools for predicting AV/CV impacts	Yes	CV/AV impacts is a widely researched topic, but most of these studies rely on assumptions that may be outdated. Developing tools or a toolkit to predict the CV/AV impacts would serve as a common platform for agencies to justify investments. This was one of the topics that required such substantial resources that it could not be funded within the resources that were already available, indicating the need for a higher level of investment.
2.3	CV/AV applications for maintenance fleets	Yes	CV/AVs have great potential in maintenance fleets, such as snow removal, work-zone dampeners, etc. Some of these would be even near-term owing to the controlled environments they operate in.
2.4	Relationships of Connected Vehicle and Automated Vehicle systems.	Yes	Given the importance of taking a holistic view that treats the infrastructure and the vehicles as portions of an integrated system rather than as distinct systems, there needs to be some basic research identifying the opportunities and challenges of both scenarios.
2.5	Traffic control strategies with consideration of AV	Maybe	Given that legacy vehicles will still dominate the traffic mix for the foreseeable near- and medium-term, this research could wait. However, there is merit to researching the impacts of CAVs on existing traffic control strategies and how those strategies can be enhanced to support mixed traffic including CAVs and conventional vehicles.
2.7	Geometric design concepts for AV systems	Maybe	Given that legacy vehicles will still dominate the traffic mix for the foreseeable near- and medium-term, this research could wait. However, there is merit to researching alternative design concepts for AV-only facilities, such as dedicated AV lanes.

Sl. No.	Title	Still Valid?	Comments
2.9	Workforce capability strategies for state and local agencies	Yes	In most cases, the agency workforce that is affected by CAVs is broad. For example, it could impact traffic engineers, planners, TIM-responders, emergency maintenance personnel, work-zone contractors etc. Detailed study of implications on each of these categories would entail a significant effort. The current funded roadmap deals with implications on TIM-responders, and is covered under NCHRP 20-102(16).
3.1	Including consideration of AV systems in the regional planning process	Yes	The team also sees that expanding the scope beyond AVs, to include implications of MOD and shared mobility on regional planning process is also important. NCHRP 20-102(09) formed a good first step in this series, but it was limited in scope. This is a resource-intensive activity that needs additional resources invested.
3.2	Assessing transportation system impacts of CV/AV	Yes	This is still one of the high-priority research needs that requires on-going and in-depth research. While topic 2.2 focused on developing the tools, this topic focuses on specific impacts summarized for different scenarios of CV/AV deployment. Research projects, such as NCHRP 08-117 (pending) and USDOT-funded "Benefits estimation framework for Automated Vehicles," are conducting some of this research, but are only taking the first small steps of many that will be needed, and the first small investments out of a larger total that will be needed.
3.3	Effects of AV/CV on land use, travel demand, and traffic impact models	Yes	
4.3	Benefit-Cost analysis of AV transit systems	Yes	This research need is still very relevant to public transit agencies to plan their investments. Although some of this is partially covered under certain TCRP J-11 Task Orders, a dedicated study assessing the benefits and costs of automated transit systems, including LSAVs, is important.

5. NEXT STEPS

In this task, the project team reviewed the research roadmap developed for AASHTO on Connected and Automated Vehicles in 2015, based on the current research landscape, and developed a commentary. In addition, the commentary also evaluated, at a high-level, the completed, on-going and planned research that came out of the previous roadmap. In the next task, the team will use this commentary and gaps analysis to develop a catalog of research needs for NCHRP to consider. The catalog will include inputs from the following sources:

1. Gaps analysis and research roadmap evaluation conducted in this task
2. Research needs put forth by the TRB Forum on Preparing for Connected and Automated Vehicles
3. Analysis of the state-of-the-art of the industry based on existing and upcoming publications, market analysis and participation in ITS America, ITS World Congress and AVS conferences.
4. Analyses of the research conducted by the U.S. DOT, the state research programs, pooled fund projects, the University Transportation Centers and others.

Please note that the analysis conducted in this task and the commentary provided in this report are based on authors information about individual projects. On-going project information is taken from pre-published and Work-in-Progress reports, which may change over time.

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