NCHRP 20-24(98)
Connected/Automated Vehicle Research Roadmap for AASHTO

Deliverable 2

Research Roadmap

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Project Overview

Connected and Automated Vehicle (CV/AV) technologies continue to advance towards introduction into public roadway systems. More than ten states now have significant CV pilot programs, allow AV testing on public roads, and/or are in the planning stages for AV/CV programs, projects, and deployments. However, there are still a variety of open questions and issues that need research, planning, and resolution at state and local transportation agencies to enable successful deployment of CV/AV. This project is assessing those open issues and developing a roadmap of future research projects and efforts that AASHTO, U.S. DOT and related groups should pursue. There are four tasks in the project. First, the research team compiled a catalog of institutional, legal, policy, and operational issues related to CV/AV technologies that will affect agencies and the public. The catalog was narrowed to critical issues designated for near term research by consolidated rankings by the panel. These highest-ranked issues were consolidated into projects, with description of goals, scope, anticipated outcomes, budget, schedule, and linkages to associated research and efforts undertaken by others. A procedure for maintaining and updating the roadmap will be developed following consensus on the content of the projects. Finally, the project will be summarized in PowerPoint slides (executive summary and long-form) that can be used by AASHTO and member agencies in disseminating the information to decision-makers, partners and stakeholders.

Catalog of Relevant Issues

In the first task, we identified a comprehensive list of unresolved issues related to AV/CV that are known at this time and relevant to state and local agency owner/operators. These issues were clustered into several categories:

- Institutional and policy
- Operational
- Legal
- Planning

Within each area, sub-clusters were identified that served to group the issues further into common topical areas. Over 100 potential topical areas were identified. The panel members were then asked to attribute importance to each issue. Based on these consolidated rankings, topics that were supported by at least half of the members of the project panel have been expanded into more complete research project descriptions by grouping issues that are closely related. We identified four general subject clusters:

- Institutional and policy
- Infrastructure design and operations
- Planning
- Modal Applications

Twenty-three project activities were identified, addressing over fifty individual issues from the original catalog (approximately half). The focus in this document is on the subject matter of the individual research topics rather than on the processes for implementing the results of these projects and for coordinating activities among the states and with other levels of government. Those considerations will be addressed in the next deliverable, dealing with the maintenance of the roadmap and implementation of the results.

Institutional and Policy Projects

Seven projects were identified in the area of institutional and policy issues:

Project	High Level Description of Outcomes	Schedule/ budget	Urgency
1.1 Implications of Automation for Motor Vehicle Codes	Recommendations for changes to laws and regulation of motor vehicle codes to address AV technologies	18 months, $500 K	Resolution of major impediment to AV deployment
1.2 Business models for CV/AV infrastructure deployment	Guidelines for investment decisions based on public and private benefits	18 months, $750 K	Resolution of major impediments to CV/AV deployment
1.3 Public agency actions to facilitate CV/AV implementation	Recommendations for policy actions with impact assessment of each	12 months, $500 K	Resolution of major impediments to AV/CV technologies
1.4 Harmonization of state regulations	Compendium of regulatory issues and action plan for resolution	24 months, $500 K	Medium – will provide tools for second-wave states
1.5 Federal-state-local boundaries of responsibility	Recommendations for actions to resolve ambiguities	18 months, $250 K	Medium – higher levels of automation and broader CV penetration will require resolution
1.6 Lessons learned from other transportation technology roll-outs	Recommendations for how to improve upon past lessons learned	12 months, $250 K	Early guidance may help early adopters of CV
1.7 Lessons learned from CV Pilot Deployments	Consolidated lessons from CV pilots to inform other agencies	12 months, $250 K	Pending completion of first wave of CV pilots

Infrastructure Design and Operations

Ten projects were identified in the area of infrastructure design and operations:

Project	High Level Description of Outcomes	Schedule/ budget	Urgency
2.1 Roadway infrastructure design	Recommendations for infrastructure elements to improve AV performance	18 months, $750 K	Resolution of potential impediment to AV deployment
2.2 Tools for predicting AV/CV impacts	Models for use in assessment of AV/CV deployment systems	36 months, $3 M	Foundation for evaluations needed for other projects
2.3 CV/AV applications for maintenance fleets	Agency recommendations for bundle of apps relevant to maintenance fleets	12 months, $100 K	Narrow niche application, but possible "low hanging fruit"
2.4 Relationships of Connected and Automated vehicle systems	Report on how CV infrastructure can support AV operation	12 months, $250 K	Medium – higher levels of automation and broader CV penetration will require resolution
2.5 Traffic control strategies with consideration of AV	Concepts for revamping or enhancing traffic control with AV systems	36 months, $1.5 M	Needs early start, but later phases are linked to tools and model development
2.6 Dedicated lanes for CV/AV operation	Report assessing the B/C analysis	18 months, $500 K	Dedicated lane facilities are high probability early adopters
2.7 Geometric design concepts for AV systems	Recommendations for roadway design modifications facilitating AV	18 months, $500 K	Medium
2.8 Cybersecurity implications of CV/AV on state and local operating agencies	Primer on cybersecurity issues and needed agency actions	12 months, $250 K	Critical
2.9 Workforce capability strategies for state and local agencies	State of the practice summary and recommendations for future staffing	18 months, $150 K	Medium
2.10 Data management strategies for CV/AV applications	Recommendations for agency actions to maintain incoming and outgoing data	24 months, $500 K	Following CV pilot deployments will enhance the quality of the recommendations

Planning Issues

Three projects were identified in the area of transportation planning:

Project	**High Level Description of Outcomes**	**Schedule/ budget**	**Urgency**
3.1 Including consideration of AV systems in the regional planning process	Algorithms and tools for modifying planning models; sample results	36 months, $1.5 M	Very limited existing tool set for predicting impacts
3.2 Assessing transportation system impacts of CV/AV	Predictions of B/C impacts of CV/AV technology in various environments	24 months, $1.5 M	Important for policy formulation, but depends on new tools
3.3 Effects of AV/CV on land use, travel demand, and traffic impact models	Algorithms and tools for modifying land use and travel demand models; sample results	18 months, $1 M	Follow results of the regional planning model project

Modal Applications

Three projects were identified in the area of modal applications:

Project	**High Level Description of Outcomes**	**Schedule/ budget**	**Urgency**
4.1 Impacts of transit system regulations and policies on AV/CV technology introduction	Recommendations for changes to regulations to encourage innovation	12 months, $150 K	Foundational to facilitate AV transit projects
4.2 AV/CV applications for Long-haul freight operations	Recommendations and plan of action to address challenges	9 months, $150 K	Foundational to facilitate AV freight projects
4.3 B/C analysis of AV transit systems	Analysis of AV transit scenarios and comparative assessment with traditional transit systems	18 months, $500 K	High probability of AV transit systems in controlled environments to be near-term applications

Allocation of Potential Projects to the Roadmap

We have made preliminary estimates for the duration, timing, and budget for each project as shown in Figure 1.

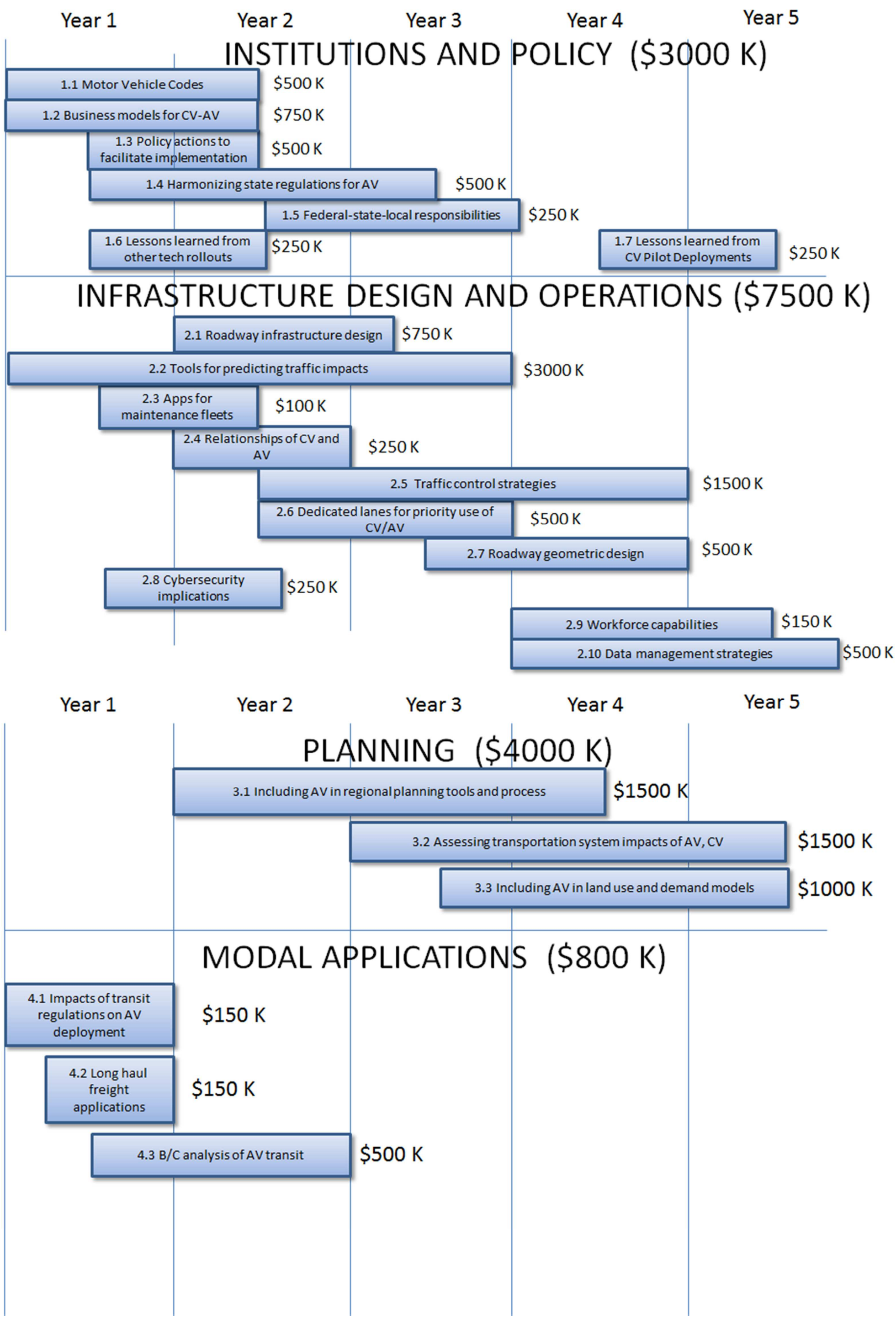

Figure 1. Research projects roadmap

Most projects do not have strong dependencies with others, but some have dependencies on other happenings such as the CV Pilot Deployments that are pending starting in 2015. One notable strong dependency is the development of simulation tools for system planning and operations (Projects 2.2 and 3.1) before impact analysis and integration of AV/CV into the long range planning process and the economic assessments of CV/AV impacts.

With some roughly linear allocation of task budgets to the duration of each project, the year-by-year funds required appear as follows:

Year 1:	$3.0 M
Year 2:	$4.0 M
Year 3:	$4.4 M
Year 4:	$2.9 M
Year 5:	$1.0 M
Total:	$15.3 M

This assumes that projects can be funded incrementally each year to accomplish some milestones. If all funds for projects starting in a given year must be allocated at the project start year, then the funds would have to be allocated as follows:

Year 1:	$6.65 M
Year 2:	$4.75 M
Year 3:	$3.0 M
Year 4:	$0.9 M
Year 5:	$0 M
Total:	$15.3 M

Evaluation of options for NCHRP project sponsorship

NCHRP has indicated in principle the willingness to fund up to $1 M of research per year for five years, which is less than one-third of the resources needed to fund the projects identified in this Roadmap. The first year of this program is scheduled to be contracted in mid 2015 with an initial allocation of $1 M. We could find no simple solution to selecting projects to fit within the NCHRP 5-year, $5-million plan. The main challenge with identifying which projects could be allocated to NCHRP is the contracting mechanisms and continuity of project teams. If NCHRP pursued several of the research topics in year 1, funding just a portion of each scope of work, the second and third years' allocations of $1 M each would not be sufficient to finish all projects started in year 1. For example, consider the following potential action plan for year 1:

1. Fund tasks 1 and 2 of project 1.2 (business models) for $250 K
2. Fund initial tasks of project 1.3 (policy actions) for $250 K
3. Fund initial tasks of project 1.4 (state regulations) for $125 K
4. Fund tasks 1 and 2 of project 2.2 (tools for assessing impacts) for $250 K
5. Fund initial tasks of project 2.8 (cybersecurity) for $125 K

Other priority projects in the Roadmap could be undertaken by other agencies (USDOT or pooled fund studies), or deferred. For example, the modal applications projects could be submitted for TCRP funding.

The above initial allocation of projects covers a variety of efforts, but requires $2.625 M of funds in year 2 to continue these projects, not including the additional funds that will be needed to start new projects (1.5, 2.1, 3.1, etc.). Based on the contracting mechanism, it would not be easy to transfer a project from NCHRP support to USDOT or other sponsorship without the delays associated with re-competing or re-contracting. If NCHRP and associated agencies can resolve these kinds of contracting issues, then it could be reasonable for the NCHRP program to fund the initial efforts (literature review, summary of state of the practice, workshops with experts, etc.) of major project tracks and have the subsequent analysis and implementation phases of these projects funded by USDOT or others. However, if the subsequent phases need to be re-competed there will be serious inefficiencies for both sponsors and contractors.

Another approach could be for NCHRP to concentrate on the small projects (less than $500K each). These project budgets sum to $5 M, but are not evenly spaced across the five years of $1 M per year allocations. The larger projects could then be funded directly by DOT or by the states through existing or new pooled fund studies.

Detailed Topic Descriptions

In this section, each of the twenty-three projects identified above are characterized in much more detail. Each topic description follows a common general outline:

1. Problem statement – what research problem needs to be solved and why (why it's important and what opportunities are enabled if the issues are addressed)

2. Research project task outline – what the research team needs to do

3. Anticipated deliverable(s)

4. Resource estimate – person-months and calendar-months of effort and rough dollar estimates

5. Urgency/timing – is it needed right now or can it be later? Does it need to come before or after some other project?

The topics have been grouped and numbered according to the following high-level categories:

1. Institutional and Policy Issues
2. Infrastructure Design and Operations
3. Planning Issues
4. Modal Applications (transit, trucking)

Each project title also indicates which issue number(s) were ranked highly by the project panel and consolidated together to form the project description.

1. Institutional and Policy Issues

1.1 Implications of Automation for Motor Vehicle Codes (original 3.1.1, 3.2.2, 3.2.3)

Research Problem Statement:
Existing motor vehicle codes have been developed based on implicit assumptions about drivers maintaining continuous involvement in the driving task and continuous responsibility for 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 so that manufacturers will be able to develop a single automated driving system for use in all jurisdictions.

Task Outline:
This project should proceed from identification of existing laws and regulations that may need reconsideration as CVs and AVs become more widely used to focusing on specific recommendations for how these codes should be changed (and how soon). Although the primary focus should be on state laws and regulations, examples of local statutes and regulations should also be considered.

(1) Identify the aspects of existing motor vehicle codes and regulations that may need to be modified when the role of the driver changes with the introduction of automated driving capabilities. Consider also a broader range of laws that extend beyond the motor vehicle codes into other related domains. Examples are expected to include:
  - Prohibitions on mobile device use because of distraction
  - DUI and open container of alcohol restrictions
  - Prohibitions on leaving children alone in vehicles
  - Requirements for how drivers exchange information after crashes
  - Determining who has responsibility for post-crash actions when there is no driver (unoccupied vehicle, freight vehicle, or automated taxi with non-driving passengers)
  - Determining who is charged with points for violations of traffic rules when the vehicle is automated
  - Allocating responsibility between users and manufacturers when a vehicle is reconfigured by its user to violate traffic laws or adjust to local conventions or common practices
  - Setting requirements for managing and protecting privacy of event data recorder (EDR) data

(2) Identify the laws and regulations that could potentially be rendered obsolescent or obsolete through widespread use of connected vehicle technology, with widespread exchange of real-time data between vehicles and infrastructure and back-office entities.
  - Protection of personal privacy versus law enforcement desires for more information

(3) Develop recommendations, backed up with reasons, for how these types of laws and regulations should be modified. Set priorities for which modifications are needed urgently to

avoid delaying imminent deployment of CV and AV systems, and identify which are less urgent but are likely to be needed at future stages of the development of these technologies.

(4) Assess the advantages, disadvantages and practicality of harmonizing the approaches to these types of laws and regulations across the country. Place this in the historical context of the evolution of automotive emissions regulations and other regulations that were initially diverse but were eventually harmonized, and develop recommendations for how such harmonization could best be facilitated in the case of CV and AV systems.

<u>Deliverables:</u>
Report identifying the types of laws and regulations that need to be reconsidered, with recommendations for how they should be changed. This should include recommendations regarding the feasibility of seeking national harmonization in each area, with explanations of the reasoning behind each recommendation.

<u>Resources:</u>
18 person months, with expertise in motor vehicle codes, transportation policy and current status of AV regulations among the states. 18 months. $500 K

<u>Urgency:</u>
This is urgently needed because it addresses one of the earliest potential impediments to the practical deployment of CV and AV systems, so it should be started in the first year. The answers to the questions raised in this project will be needed before private companies will be able to justify heavy investments in deploying and operating the systems.

1.2 Business Models to Facilitate Deployment of Connected Vehicle Infrastructure to Support Automated Vehicle Operations (original 1.3.6, 2.3.2, 4.3.3)

<u>Research Problem Statement:</u>
Connected vehicle technology will be essential to support the operation of automated vehicles in ways that will generate societal benefits rather than disbenefits. Different jurisdictions will have varying levels of interest in deploying CV infrastructure, based on varying perceptions of the benefits that they will gain from CV systems. Limited availability of the CV infrastructure will seriously impede the ability of AVs to operate everywhere and is likely to deter growth of the market for AVs. How should this problem be addressed, to provide policy frameworks and/or business models that can facilitate widespread deployment of the needed CV infrastructure?

<u>Task Outline</u>:
This project needs to start from a basis of solid analysis showing the importance of CV technology to enable AV systems to produce societal benefits, and then explore how to deploy the needed CV infrastructure.

(1) Review and summarize existing authoritative research results to show the differences in traffic flow dynamics (and hence congestion, energy use and pollutant emissions) associated with autonomous versus connected vehicle automation systems at various levels of automation. Based on these results, estimate the net difference in societal benefits of AV implementation with and without CV capabilities for a variety of representative deployment environments (large and small metropolitan regions, intercity corridors with different traffic volumes…). Assess these separately for I2V and V2V cooperative automation (for which the infrastructure requirements are likely to be substantially different). For cases in which the existing literature does not provide sufficient information about the differences, perform additional modeling and simulation studies to produce refined estimates.

(2) Define how the requirements for CV systems to support AV operations could potentially be more stringent than they would be for other ITS applications, in ways such as:
- Limited tolerance of holes in communication coverage when driving from one jurisdiction to the next
- Higher availability requirements based on safety and productivity implications of the loss of communications by the AV applications
- Need for additional data elements beyond the minimum required BSM Part I data elements that will be required for cooperative collision warnings under NHTSA regulations
- Enhanced cyber security needs.

Based on considerations such as these, identify the extent to which AV usage could impact the costs of deploying and/or operating the infrastructure elements of both I2V and V2V cooperative systems.

(3) Define potential business models for deployment of the CV infrastructure needed to support AV use of CV technology, accounting for public agency sensitivity about providing others with access to their traffic signaling infrastructure. These could include:
- Combinations of designing, building, owning, operating, and maintaining the CV systems by the public agencies themselves

- Franchising or contracting out to third parties
- Offering right-of-way access to third parties in exchange for them providing the CV infrastructure
- Other forms of public-private partnerships in which the AV industry or AV operators would finance the CV infrastructure costs based on their own direct benefits
- Relying on cellular infrastructure as available rather than deploying DSRC, considering the potential differences in communication capabilities and system performance as well as costs and responsibilities for the public agencies.

(4) Based on the findings from the previous tasks, develop recommendations for what actions states should take regarding implementation of both I2V and V2V connectivity infrastructure to support AV operations, addressing topics such as:
- Criteria states should use to prioritize locations for I2V and V2V CV infrastructure deployment
- How the CV deployments should be financed (what business models for what operating environments) based on the levels of implementation costs and of societal benefits relative to direct private user benefits.

Deliverables:
Report on study findings, with recommended guidelines for decision makers to use in making their investment and policy decisions.

Resources:
3 person-years of effort, with strong understanding of CV and AV technology and applications and their costs and benefits, combined with transportation policy and finance knowledge. 18 months. $750 K

Urgency:
High urgency because of the need to make imminent decisions on the earliest CV infrastructure deployments (initiate in first year).

1.3 Identification of State and Local Policy Actions That Could Facilitate Implementation of CV and AV Systems (original 1.1.2 and 1.2.1)

Research Problem Statement:
Connected and automated vehicle systems are likely to have societal benefits that are not captured in market decision making about acquiring and operating systems based on private cost-effectiveness considerations. State and local governments need to know what policy actions they can take to stimulate the development of markets for CV and AV systems so that the societal externalities can be internalized in market decisions.

Task Outline:
This project should follow a basic flow from identification of impediments to market-based deployment of CV and AV systems to identification of possible policy actions to overcome those impediments to prioritization of policy actions based on their expected impact and feasibility:

(1) Identify the mismatches between societal benefits and individual private actor benefits from implementation of CV and AV systems, based on the project team's knowledge of the literature on CV and AV systems and interviews with key experts and stakeholders.

(2) Identify a broad range of policy actions that state and/or local agencies could use to better align the interests of private actors (individuals and corporations on both the supplier and user sides of the markets) with the broader public interest in achieving benefits in traffic safety, traffic congestion reduction, and savings in energy and criteria pollutant emissions. These are expected to include actions such as:
   - Preferential access to HOV/HOT lanes (including reduced toll rates)
   - Tax and other financial incentives (waiving taxes on incremental costs for AV systems or subsidizing their purchase)
   - Providing connected vehicle communication infrastructure
   - Improving road markings and signage
   - Developing or facilitating technology incubators or testing facilities
   - Encouraging new forms of public-private partnerships
   - Sponsoring pilot testing or deployment programs
   - Acquiring AVs for state fleet operations
   - Changing laws regarding direct vehicle sales by manufacturers versus sales only by dealers.

(3) Assess each of the suggested policy actions for cost, political feasibility and likely impact on market decisions that could accelerate deployment of CV and AV systems.

Deliverables:
Report with recommended policy actions and estimates of their expected costs and impacts on deployment of both CV and AV systems.

Resources:
2 person-years over one year, with expertise in transportation policy and in CV and AV technology capabilities, costs and benefits. $500 K

Urgency:
Near-term priority because of lead times needed to implement actions based on the recommendations developed in this project and their importance as stimuli to deployment. This should be during the first two years of the program.

1.4 Harmonization of State Goals and Regulations (original 1.4.1)

Research Problem Statement:
States prize their independence and autonomy and often adopt different policies and strategies to deal with common issues. If the states adopt significantly different approaches to CV and AV deployment, it is likely to make it very difficult for these technologies to be implemented. It will not be technically or economically viable for vehicle developers to design their systems to change their operations whenever they cross state borders, so the deployment of the technology will be stalled if the states are inconsistent in how they decide to regulate them. It is going to be important to determine how to forestall such a problem by bringing the interested states together to seek agreement at some level on how to develop regulations that are sufficiently harmonized that they will not impede deployment of the technologies.

Task Outline:

(1) Identify the full range of areas affecting CA and AV deployment in which states have current regulations or may develop regulations in the future. Consider at a minimum areas such as:
   - Restrictions on access to state infrastructure by non-state organizations
   - Rules on protection and sharing of data acquired using state infrastructure or resources (considering intellectual property and privacy issues)
   - Rules for state participation in public-private partnerships
   - Motor vehicle registration rules
   - Driver licensing rules
   - Post-crash reporting rules
   - Restrictions on driver behavior (use of mobile devices, DUI and other alcohol and drug related rules, specific rules of the road for interacting with other road users…)
   - Implementation of national standards such as MUTCD
   - Regulations specific to automated driving system testing and/or public operation.

(2) Identify the primary areas in which states are already inconsistent in how they handle these topic areas, with priority based on the potential impact on national interoperability of CV and AV systems. Contact key state government experts in the states that have been identified as being inconsistent with each other and interview them about the reasons that their states have chosen their respective approaches and about what possibilities they see for flexibility in changing their approaches.

(3) Based on the results of the interviews in (2), define recommendations for how to harmonize regulations nationally and what those harmonized regulations should say, based on the principle of ensuring the minimum level of regulations needed to support national consistency and safety. (This is a less stringent test than supporting national interoperability, which would require much more detailed technical standards. The goal here is to get out of the way of the industry, assuming that the industry can develop the standards for interoperability as long as the states do not create regulatory barriers to that interoperability.)

(4) Define the actions that should be taken to bring together representatives of the administrative and legislative branches of state governments throughout the country to seek agreement on the appropriate level of regulations and the basic contents of those regulations.

Deliverables:
A compendium of the state regulatory issues that need to be considered to support national deployment of CV and AV technology, together with an action plan for harmonizing those regulations to a sufficient level that they will not deter industry from developing the CV and AV products.

Resources:
This is expected to require about two labor years of effort over two years by people with a strong background in state transportation regulations and a solid understanding of how those regulations affect CV and AV technologies. $500 K

Urgency:
This project has a stronger flavor of defining policy and strategy than of research, but it addresses an issue that may take a long time to resolve so it needs to be started as early as possible. This is particularly challenging since the states vary greatly in the level of attention they have given to CV and AV deployment, yet nationwide deployment is in some sense constrained by the slowest state.

1.5 Implications of CV and AV Technologies for Federal-State-Local Boundaries of Responsibility (original 3.2.1)

Research Problem Statement:
The division of responsibilities among federal, state and local government entities has developed over centuries of experience, but CV and AV technologies are likely to generate interest in changing or blurring the definition of these boundaries. It is important to understand the challenges and possibilities associated with potential changes of traditional boundaries so that the easy-to-change ones can be distinguished from the hard-to-change ones, as well as understanding which kinds of jurisdictional changes are likely to be most needed to facilitate deployment of CVs and AVs.

Task Outline:
Because the subject of jurisdictional boundaries among levels of government is so broad, it will be necessary to clearly focus from the start on the categories of jurisdictional boundary definitions that are most directly relevant to CV and AV deployment and operation. This project work should include:

(1) Identify the areas in which CV and AV technologies do not clearly fit within the long-established federal-state-local jurisdictional categories. These are expected to include, for CV systems:
- Planning, deployment and operation of infrastructure-based elements of cooperative systems that are sufficiently uniform to support national interoperability of the in-vehicle elements;
- Implementation of the supporting functions for the national CV infrastructure such as the Security Credentials Management System (SCMS), which are likely to need new organizational structures;
- Implementation and operation of transportation infrastructure systems whose life cycle costs are dominated by O&M rather than capital costs, so that the bulk of the costs are not covered by existing federal aid programs.
- NHTSA has raised the suggestion that their reach could extend into traffic signal control systems if those are cooperating with in-vehicle safety equipment (I2V systems), which could raise concerns on the part of state and local agencies that own the signal systems.

And for AV systems:
- States have already passed laws requiring their departments of motor vehicles to develop regulations that are typically NHTSA's responsibility at the national level, since they cover automated driving systems that are integral parts of the vehicles.
- State responsibilities for regulating the operation and licensing of motor vehicles are overlapping NHTSA responsibilities for regulating the safety of new motor vehicles now that software embedded in the vehicles is determining how those vehicles operate.

(2) Develop recommendations for how the current boundaries should be adjusted or re-interpreted to best support safe and economical operation of CV and AV systems:
   a. What administrative actions should U.S. DOT take to clarify its responsibilities?
   b. What administrative actions should the states take, through their coordinating mechanisms in AASHTO, to clarify their own responsibilities relative to both federal and local levels of government?

c. What kind of legislation will be needed at federal and/or state levels to cover the issues that cannot be handled through administrative actions?
d. What type of financial incentives may be useful to encourage needed shifts in responsibilities that may not be politically attractive otherwise?

<u>Deliverables:</u>
Report documenting the topic areas in which boundaries need to be redefined or clarified, with recommendations for the actions that should be taken at federal, state and local levels.

<u>Resources:</u>
One labor year, with expertise in transportation policy and government structure, as well as good understanding of CV and AV applications. 18 months. $250 K

<u>Urgency:</u>
Moderately high (Years 2-3) – although some progress can be made even before these questions are answered, these questions need to be answered as a prerequisite to implementation of higher levels of automation.

1.6 Lessons Learned from Roll-Outs of Other Transportation Technologies (original 1.3.8)

Research Problem Statement:
The implementation of CV and AV technology requires consideration of a wide range of technical, economic, institutional and societal complexities, beyond the issues that are normally encountered in transportation projects. It will be beneficial for the decision makers who need to grapple with these issues to be able to learn from the experience of their predecessors who have dealt with comparable issues in earlier roll-outs of new transportation technologies, including both successes and failures. In this way, they should be able to identify prior models to follow and traps to avoid.

Task Outline:

(1) Identify relevant prior transportation technology roll-outs that could provide lessons for CV and AV deployment efforts, considering in particular the public-private sector interactions and the network externality challenges (lack of benefits for first adopters before many more decide to adopt the technology). The preferred examples would be recent ones, but older ones may also be able to shed light. Consider at a minimum examples such as:
   - 5-1-1 Deployment Coalition
   - Intelligent transportation systems in general
   - NextGen air traffic control system update
   - Interstate Highway System
   - Electronic toll collection systems
   - High-speed rail systems (in U.S. and other countries for contrasts).

(2) For each system, define successful and unsuccessful aspects of the introduction of the technology in terms of: economic viability (cost and benefit sides), speed of implementation, customer acceptance, impacts on transportation system performance and the economy in general, and other relevant measures of effectiveness. Explain the reasons for these successes and failures.

(3) Identify what lessons each of these prior examples can teach us regarding implementation of CV and AV technology, and synthesize these findings into recommendations regarding "do's and don'ts" for CV and AV implementation.

Deliverables:
Report on the findings from this work, with recommendations for how to use these results to make decisions about CV and AV implementation.

Resources:
One labor year of experienced experts who have a long-term perspective on transportation history, policy, operations and technologies. $250 K

Urgency:
Medium urgency because of uncertainty about how strong the analogies will be between the prior examples and the current decisions that need to be made about CV and AV deployment. This can wait for the fourth year of the program.

1.7 Lessons Learned from Safety Pilot and Connected Vehicle Pilot Deployments

Research Problem Statement:

The Safety Pilot and upcoming Connected Vehicle Pilot Deployments represent the first small steps toward deployment of CV systems in the U.S. The pioneering organizations that implement these deployments are likely to learn many lessons about CV technology and institutional and other practical aspects of CV operations. It will be beneficial for other organizations around the country to learn from the experiences of the pioneers so that they can repeat their successes and avoid their mis-steps. Capturing these experiences while they are still fresh should also represent an opportunity for other agencies to reduce their perceived risk in proceeding with their own CV deployments.

Task Outline:

(1) Review the documentation of the Safety Pilot and CV Pilot projects, with particular emphasis on the general lessons that could be applied in other locations (not peculiar to the specific first deployment sites).

(2) Develop a questionnaire for the Safety Pilot and CV Pilot project leaders, highlighting the topics that are expected to be of interest to other localities considering similar CV deployments, such as:

   a. What were the biggest surprises you encountered in your project?
   b. What have been your biggest successes and failures?
   c. If you were starting the project now, what would you do differently from the way you did it originally?
   d. What is the most important advice you can give to an agency considering following in your footsteps?

(3) Visit each of the pioneering deployment sites to meet with the leaders of these projects and interview them about their experiences and the advice that they would offer to other agencies that are considering their own CV deployment projects.

(4) Document the results of this investigation and conduct an outreach campaign to explain them to a wide range of national stakeholders through participation at key national and regional meetings and write-ups for the most suitable trade publications and online resources.

Deliverables:

Report on the findings from this work, including outreach to disseminate the information among the stakeholder community.

Resources:

One labor year of experienced experts who have intimate knowledge of the connected vehicle program and a good understanding of how transportation agencies operate. $250 K

Urgency:

Medium urgency, balancing the need for disseminating the information with the restriction that meaningful data cannot be gathered until the first round of CV pilots have been operated for a while.

2. Infrastructure Design and Operations

2.1 Roadway infrastructure design considerations for operation of automated vehicles (2.2, 2.2.1)

<u>Problem Statement :</u>
State and local agencies are responsible for deploying and maintaining traffic control devices, markings, and signs, and designing roads for safe operation of vehicular traffic. A long history of research, development, and testing has led to current standards and practices for materials, placement, and design of these roadway features and the road itself. Due to a variety of outside influences, maintenance of markings and controls is sometimes challenging for agencies to prioritize and fund. All agencies use similar design principles from the MUTCD and the AASHTO "green book", but no jurisdiction implements road facilities in exactly the same way. Active traffic control strategies include the traffic signal, ramp meter, lane use display, and variable speed display. Other active displays might indicate the status of oncoming light-rail trains or preemption from public safety vehicles. New types of devices are constantly under development, including a wide range of new and innovative pedestrian crossing applications. Displays are not placed in uniform locations, nor are they oriented the same way in each jurisdiction (horizontal or vertical, and mast arm versus span wire).

Currently, AV technologies are being developed for highway operation, and some private developers are planning for allowing autopilot systems to be used in special applications in closed campuses. Human drivers have good capacity for adaptation in situations where markings and guidance may be lacking and make real-time complex inferences about acceptable behaviors even when they cannot consistently see the displays, such as when they might be obscured by a large truck or a setting sun. Automated driving systems must be programmed in a variety of ways (vision algorithms, databases/maps of marking locations, allowable routes, etc.) to mimic these human capabilities.

While standards do exist for marking and signs, there is still enough variability in allowable types that it is likely to be challenging for AV operations. Road widths, curvature, ramp length, and hundreds of other attributes vary from jurisdiction to jurisdiction. There is a need to understand what types of signs, markings, and devices are currently "easy" for AV applications and which are difficult and work to develop standards that could assist both AV and human drivers. For example, markings such as "QR codes" may be intelligible to machines, but humans can't read them at all. In addition, research is needed to identify any special markings or devices and roadway designs that could enhance AV/CV applications in general but in particular in work zones and emergency management areas. The research should identify any actions that could reduce the need for periodic maintenance or improve operation in areas that are burdened by freeze/thaw cycles or other effects that make maintenance problematic.

<u>Task Outline:</u>
The research team will work with AV system developers to summarize their current approaches to handling traffic signs, signals, and devices. Review of the literature on vehicle automation will be useful in expanding the base understanding of the principles of AV operation. Current

vendors of marking and signing materials will be engaged for their feedback on technology enhancements and their vision for the upcoming years of product development. Existing research and state-of-the-art in retro-reflectivity and other innovations in signing and marking and roadway design will be summarized. The researchers will review and summarize principles and regulations from the MUTCD on signing and marking and the AASHTO "green book" to identify areas where modifications to standards could be beneficial to automated vehicles (and regular drivers as well) and improve the consistency of markings and signs and roadway features across the states. The team will recommend a series of next steps in an action plan for testing the recommended concepts in test facilities and on real-world road systems. The recommendations will include concepts for funding the replacement of signs and improvements to markings necessary for AV operation, and concepts for how maintenance of signs and markings and roadway features can be improved (i.e. snow and foliage removal, detection of marking deterioration, ramp curvature, intersection design).

Deliverables:

- Phase I: Summary of state-of-the-art and state-of-the-practice in marking /signing, and geometric roadway design and relevant challenges for AV operation
- Phase II: Analysis and recommendations of next steps

Resources:
Two and a half person-years, with a combination of expertise on current geometric design practices, MUTCD, signage, road markings and automated vehicle sensor technologies. $750 K over 18 calendar months.

Urgency:
Several dedicated test facilities for AV technologies are currently being developed, although most AV system developers are already testing in real-world environments. The foundational research should probably start in year 1. Implementation of the testing action plan developed in Phase II is recommended to follow in years 3-5, based on availability of additional funding.

2.2 Development of Tools to Predict the Impacts of CV and AV Systems on Highway Operations (original topic 2.2.7)

Research Problem Statement:

Among the primary expected benefits of CV and AV technology on the transportation system are significant increases in traffic efficiency and capacity. Modest investments in the CV and AV infrastructure could potentially substitute for larger investments in traditional methods of increasing transportation system capacity. Transportation engineers need to have new models and tools that they can use to design their physical infrastructure and traffic control systems to take advantage of these opportunities.

Task Outline:

This project should start with identification of the ways in which CV and AV technology could improve capacity and stability of traffic flows and then proceed to the definition of the models to quantify those benefits. The expected impacts on infrastructure and traffic control system design should then be shown through case studies using those models.

(1) Identify the types of influences that CV and AV technology are expected to have on traffic flow capacity and stability, including but not limited to:
   - Communication of variable speed limit values that maximize flow through a highway bottleneck directly to the drivers (CV) or to the I2V CACC systems on the vehicles (AV).
   - Communication of traffic signal phase and timing (SPaT) information to vehicles to enable the drivers (CV) or the vehicles' I2V CACC systems (AV) to drive at a speed that minimizes stops and delays.
   - Communication of vehicle state information among vehicles to enable V2V CACC with closer than normal coupling of vehicle motions (CV + AV)
   - Communication of vehicle state information among vehicles to facilitate merge and lane change coordination to reduce the friction caused by merging (CV +AV).

(2) For each of the types of influences on traffic identified in (1), define the type of traffic modeling representation that will be needed to predict its effects on traffic flow capacity and stability. This is likely to differ based on the type of system under consideration and whether it is intended to be used on limited-access highways or on signalized arterials. For some applications, macroscopic models may be appropriate, while others are likely to require microscopic models.

(3) Define the specifications for the models that need to be developed, including which CV and AV applications are to be represented and which measures of effectiveness are to be predicted. This is likely to require development of more than one model, considering the differences between the methodologies that have to be applied to predict microscopic traffic impacts and macroscopic regional impacts. The model specifications should be defined so that the models can be used in complementary fashion, so that the outputs of the microscopic model(s) can be used as inputs to the macroscopic model(s). At a minimum, the set of models should be specified to predict effects of different market penetrations of CV and AV applications, individually and combined, on:
   a. Traffic flow capacity, delays and travel times
   b. Energy consumption and CO2 emissions

    c. Emissions of criteria pollutants

(4) Determine the most effective way of coding and implementing the needed models, based as much as possible on use of existing transportation modeling tools and then adjusting them using APIs and software development kits to incorporate the new CV and AV elements. Define how to realistically represent the effects of changes in vehicle-following dynamics, in aerodynamic drag, in lane keeping performance, in crash rates, and in knowledge of the actions of other vehicles associated with the CV and AV systems (individually and in combination) within the frameworks of the existing tools.

(5) Implement the new code and test it for a variety of scenarios, including highway and urban traffic in several representative environments. As part of the testing and verification process, convene an independent panel of experts to review the models and the model predictions in detail and to give a peer review approval before the models are used to make predictions in support of deployment decisions.

(6) Conduct modeling case studies on representative traffic networks using the tools developed in the earlier subtasks, showing the differences before and after the CV/AV alternatives were applied. Based on these results, define guidelines for predicting the CV/AV effects on traffic under several representative scenarios.

<u>Deliverables:</u>

- Validated models of impacts that can be used by other researchers and by public agencies that are trying to make decisions about CV/AV deployment and operation, implemented in re-usable software.
- Documentation of the models needed to show the traffic flow effects of CV/AV and documentation of the calibration data.
- Documentation of the results of the case studies, with recommendations regarding their significance for the modification of design guidelines for roadway infrastructure and traffic control systems.

<u>Resources:</u>

This is a substantial project that is likely to require about 10 person-years of professional effort, with a strong emphasis on microscopic traffic modeling and in-depth understanding of the CV and AV technologies to be able to model them accurately. It should take about two years. $3 M

<u>Urgency:</u>

This is urgent to provide the knowledge base to enable transportation infrastructure agencies to prepare themselves for CV and AV impacts, so it needs to start as early as possible. It also provides the tools needed to support other projects such as 2.6.

2.3 CV/AV Applications for State and Local Maintenance Vehicle Fleets (2.1.8)

Research Problem Statement:
Large state and local agencies have significant fleets of maintenance vehicles for equipment and field infrastructure repairs, construction, snow removal, etc. Since these fleets are under the direct control of the agency, they could be a valuable resource for CV/AV concept testing and benefits evaluation. Many agencies already use GPS tracking for vehicle location. Some states have already begun testing Level 1 AV devices. A variety of technologies have been tested to aid vehicles that perform snow removal and salt application. Implementer agencies need experiences from innovator agencies in applying CV/AV applications to core agency functions.

Task Outline:
The research team will review the array of CV/AV applications and concepts and identify those combinations that would be most applicable as a “bundle” for state and local agency maintenance fleets. The team will review past and ongoing research in maintenance applications and summarize the state of the art. The team will identify any gaps that need additional work for applying AV/CV concepts to maintenance vehicle operation. The team will recommend a series of next steps in an action plan for development, implementation and testing of the recommended concepts in test facilities and on real-world road systems.

Deliverables:
- Report on CV/AV applications for state and local maintenance fleet vehicles
- Plan for next steps to implement recommendations

Resources:
Five person-months, with expertise in highway maintenance activities and knowledge of the state of the art on automation of maintenance functions. $100 K over 12 calendar months.

Urgency:
A fairly self-contained study that builds on existing knowledge, with no significant dependencies on other work. Years 1-2, but could be moved later to accommodate other areas of emphasis.

2.4 Relationship Between Connected and Automated Vehicle Systems (original 2.3.1, 2.3.3, 2.3.4, 2.3.5)

Research Problem Statement:

Both connected and automated vehicle systems involve equipping vehicles and the roadway infrastructure with new technologies, and the decisions about deployment of those technologies need to be based on some degree of cooperation between the vehicle industry and the agencies that own and operate the roadway infrastructure. The CV and AV interests are not yet fully aligned with each other, despite the obvious synergies between them. It is necessary to define the relationship between CV and AV operations in sufficient depth that these synergies can be quantified clearly enough to be understood by decision makers (showing the transportation system performance implications of CV without AV, AV without CV and combined CV and AV). Considering the resource limitations of most public infrastructure agencies, this study also needs to consider alternative models for implementing the infrastructure elements that will be needed (through private business models and public-private partnership arrangements).

Task Outline:

This project requires consideration of a mixture of technical and policy issues, which are closely intertwined in the relationship between CV and AV systems.

(1) Identify the requirements that AVs place on the supporting CV technology and infrastructure in general terms such as geographic coverage, connection latency, bandwidth, and availability compared to the requirements needed to support other CV applications. In particular, if the AV operations are only anticipated in specific locations (individual corridors, highways, or urban or campus settings), define the CV infrastructure needed to cover those locations. Begin with a baseline assumption of 5.9 GHz DSRC, but consider other possibilities if they appear to be capable of meeting the requirements to support AV services. Define how these communication capabilities will have to be provided (what additional technologies) and estimate the costs of deployment and operation of the communication system.

(2) Analyze the ability of 5.9 GHz to meet the AV requirements if the spectrum needs to be shared with general WiFi users. If this does not appear to be adequate, identify other communication alternatives that could be used in combination with or in place of 5.9 GHz DSRC to meet those needs, including advanced cellular communications and line-of-sign infrared systems.

(3) Define a range of possible organizational frameworks for deploying and operating the communication infrastructure defined in (2) above. Include definition of the managerial and financial responsibilities of the different kinds of organizations that could potentially be involved, including state and local roadway infrastructure agencies, private cellular network operators, vehicle manufacturers, independent vehicle fleet owner/operators and other private entities, including private consortia and public-private partnerships. Define advantages and disadvantages of each of the institutional alternatives and recommend which are suitable for implementation.

(4) For the institutional models that appear to be viable, recommend how they should be structured and how responsibility and authority should be divided among the public and private sector organizations to promote efficiency and equity. Identify any ways in which

this would be different for CV infrastructure that needs to support AV operations and CV infrastructure that does not need to support AV operations, and recommend how those differences should be accounted for in the business model that pays for development and operation of the communication system.

Deliverables:
Report documenting the viable alternatives for providing CV support, including recommendations for how the different kinds of stakeholder organizations should be interacting to deploy and operate the CV communication system.

Resources:
One labor year of effort during a one year period of performance, based on a mixture of expertise in wireless communication technologies applicable to transportation, detailed knowledge of the communication requirements to support CV and AV applications, and understanding of the institutional frameworks of the road transportation industry. $250 K

Urgency:
Medium-high urgency, based on the need to start implementing the CV infrastructure relatively soon, while recognizing that the AV applications of the CV infrastructure are likely to be implemented later than many other applications. This should be in Year 2 or 3.

2.5 Traffic Control Strategies with Consideration of Automated Vehicles (2.2.2)

Research Problem Statement:

There are more than 350,000 signalized intersections in the United States. Existing controllers range from mechanical units to modern Advanced Traffic Controllers (ATC). The majority of these devices have a deployment life of approximately 20 years. This means that about 17,500 controllers are replaced annually and about 2,500 new signals are added each year. To achieve the US DOT vision of safe and efficient transportation systems a new generation of traffic signal control algorithms and controllers needs to be developed to support emerging technologies such as automated vehicles. The USDOT Connected Vehicles program and associated V2X programs in Japan and Europe provide the foundation for interactions between traffic controllers and vehicles. Much of the underlying technology, messaging, and associated functionality will remain unchanged whether the vehicle is automated or driven by a human. It can easily be envisioned, however, that AVs provide additional opportunities for synergy as well as challenges to traffic control and system operation.

There have been some re-examinations of how traffic signal control can operate with specific consideration of the information-rich environment provided by Connected Vehicle capabilities, such as the Connected Vehicle Pooled Fund Study MMITS, demonstration projects by USDOT at the Safety Pilot, and a variety of research at leading universities in the U.S. and abroad. Very little of this research has made any distinctions between AVs and human-driven vehicles. Automated shared-use (transit or taxi) vehicles may be able to provide more comprehensive routing or O-D information to the signal controller than people would be willing to provide from their private personal vehicles.

With detailed data on traffic delays, vehicle trajectories, intended maneuvers, destinations, break-downs, and other information coming from CVs, safety and operational efficiency improvements can be incorporated directly into the traffic control process. Automated vehicles rely on sensor systems of various types to provide the inputs that human drivers acquire through our eyes, ears, fingers, and bodies and synthesize into information. The human's ability to fuse information from multiple sources is unparalleled by computer systems to date. Take for example the challenge presented by four vehicles arriving virtually simultaneously at a four-way stop-controlled intersection. Human drivers negotiate the travel order using a combination of eye contact, hand signals, and vehicle movements (or lack thereof), but automated vehicles will be challenged to negotiate such situations. Interactions with pedestrians, cyclists, and permitted left turns offer similar challenges for automated vehicles that are negotiated relatively easily by the human brain's sophisticated "sensor-fusion" wetware. There are likely many modifications to the built environment that can facilitate better AV performance in parking, searching for parking, negotiating signalized intersections, downtown areas, etc.

New traffic management strategies (in conjunction with intersection designs, striping, signalization, displays, communications, and other technological changes) may be able to facilitate more rapid deployment of AVs by making it easier for automation systems to operate in more diverse situations and locations. With the benefits that AVs could offer, it is in our national interest to begin to prepare our traffic management systems and devices for automated vehicles rather than to react to their widespread deployment after the fact.

Task Outline:
The research will review the existing literature and summarize the state of the art and identify technologies that are currently in development that could be directly leveraged into test facilities. The team will then develop a new concept of operations for traffic control that considers the special needs of AVs as well as the unique data that AVs can contribute. It will be important to consider control strategies that take advantage of the fact that AVs will be phased in to the vehicle fleet over time. The research team must develop and consider strategies that take advantage of a range of penetration rates of AVs as well as infrastructure systems. This should include methods for operating individual intersections as well as operating coordinated corridor and grid systems of traffic controllers.

The products of this advanced and exploratory research will be traffic control strategies that consider low-speed urban AVs and cooperating infrastructure, evaluation results assessing the performance impacts of the strategies utilizing microscopic traffic simulation models, and a blueprint work plan for future deployment activities to apply the strategies in a field test bed and cooperative agency-operator (e.g., perhaps on a private campus). A work plan of research and development activities to transform existing traffic control hardware and software into applications that make AV driving more reliable, efficient, and safe should be included. The methodology, algorithms, and software should be engineered to be reusable by the majority of current signal system providers at both the local and central levels.

Deliverables:
- Phase I: Summary of state of the art in traffic control algorithms that consider AV/CV technologies
- Phase II: Concept of operations for AV-enabled urban traffic management strategies
- Phase III: Simulation results for implementation of management strategies
- Phase IV: Blueprint work-plan for future activities for field testing and implementation

Resources:
Four person-years at $1.5 M. Phases 1 and 2 ~$250 K; Phases 3 and 4 ~$1.25 M, over a total of 36 calendar months.

Urgency:
Phases 1 and 2 can start in years 1-3. Phases 3 and 4 are linked to other research in the roadmap.

2.6 Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles (original 2.2.8)

Research Problem Statement:

Converting existing general-purpose highway lanes to more restrictive access for use only by certain vehicles or travelers has been politically unacceptable ever since the disastrous initial attempt to convert a lane of the Santa Monica Freeway to HOV-only use forty years ago. Since CV and AV systems can work much more effectively and provide much higher lane capacity when the equipped vehicles are clustered in close proximity to each other in the same lane, these technologies provide new motivations to convert lanes from general use to more specialized uses. The issue of dedicated lanes needs to be restudied now in light of these developments, to develop more authoritative estimates of the benefits that could be gained and of the disadvantages to the general purpose road users who would be excluded from those lanes.

Task Outline:

(1) Identify the categories of benefits and dis-benefits that could be experienced by the CV/AV users of dedicated lanes and the rest of the road users who will continue to use the remaining general purpose lanes and that therefore need to be factored into any analysis of impacts. Consider factors such as the following and how they will be distributed across the population of road users:
   - Travel time or average travel speed changes
   - Traffic impacts of additional lane changes for vehicles transitioning to and from the dedicated lanes
   - Traffic flow or speed stability
   - Crash risk
   - Energy consumption
   - Perception of exclusivity or social justice bias (e.g. "Lexus lanes" argument)

(2) Define any enhancements that may be needed to the CV/AV modeling framework developed in Project 2.2 to estimate the scale of each of the identified benefits and dis-benefits and incorporate them into an existing transportation modeling framework (such as a traffic simulation tool).

(3) Identify diverse case study sites that would be useful for estimating benefits and dis-benefits by users and non-users. Select a sufficiently diverse set of case study sites that the results of the modeling work will be usable to define guidelines that agencies can use to determine whether their specific applications would merit lane dedication. These should include different levels of traffic congestion, network connectivity, availability of alternate routes and modes, spacing of access/egress points, truck traffic, and traffic patterns (core focused versus dispersed).

(4) Apply the models to the selected case study sites and assess the benefits and dis-benefits over a range of market penetrations of CV/AV technology to support the determination of which conditions are likely to produce a large enough net benefit to support a decision to dedicate a lane to CV/AV users.

(5) Identify the policy actions that need to be taken in support of lane dedication, for the cases in which the benefits appear to exceed the costs.

Deliverables:
Report describing the models and the results of the modeling exercise, showing the trends in benefits to CV/AV users in the dedicated lanes and possible dis-benefits to non-users as a function of market penetration. Include guidelines based on these results, defining which combinations of conditions appear to be amenable to dedication of lanes for CV/AV users and what policy actions the affected agencies need to take to make this feasible.

Resources:
2 labor-years of effort, based on use of models primarily developed under other projects (such as 2.2). 18 months. $500 K

Urgency:
High urgency because of the potential for dedicated lanes to provide the level of protection needed to enable automation to produce early benefits, before the technology is sufficiently mature to be able to operate safely under all road conditions. However, this cannot get far until the underlying microscopic traffic modeling and simulation tools are available, so it probably needs to wait until Year 2 or 3 to start.

2.7 Roadway Geometric Design Concepts for Operation of Automated Vehicles (2.2.3, 2.2.6)

Research Problem Statement:
The thousands and thousands of miles of roadways, over 300,000 signalized intersections, and other traffic facilities have certain design principles, features, and characteristics that assume human drivers, for better or worse. These assumptions have certain implications for vehicles that are operated by AVs instead of people. AVs rely on various sensor systems to provide artificial stimuli equivalent to those human drivers acquire through our eyes, ears, fingers, and bodies and synthesize into information. The human's ability to fuse information from multiple sources is unparalleled by computer systems to date.

Unlike people, AVs could be programmed to automatically follow re-routed lanes without lane markings, which would improve safety in work zones. However, this would require that a high-resolution digital map be developed, frequently updated, and broadcast to the AVs and the AVs would need to have highly accurate and dependable positioning systems to match their locations to the map.

In addition, AVs could eventually become better at keeping in lanes, which can reduce the necessary width, reclaiming street space for cyclists or pedestrians (or more AVs) or fitting more lanes within the existing highway pavements and structures. On-street parking may need to be relocated, pedestrian zones may need to be defined, and channelization and segregation of automated and non-automated facilities may need to be done.

New intersection and roadway designs and other technological changes may be able to facilitate more rapid deployment of AVs. Considering the potential benefits that could be gained from AVs, it is in our national interest to begin to prepare our built environment, devices, signage, and so on before widespread deployment rather than after the fact.

Task Outline:
The research team will consider a number of alternative realities that include penetration of AVs in urban centers, freeways, and arterial road systems. Workshops with roadway design and AV system experts across North America will be held to cross-pollinate ideas and ensure that regional differences in design and implementation of roads are taken into consideration.
The research should characterize the key limitations of existing infrastructure systems and facilities and identify considerations on roadway system design that will affect operation of AVs. The research should assess cost and feasibility of facility designs assessed against the estimated benefits, and principles of the AASHTO "green book" and other standard references for facility design that may need to be modified in the context of significant penetration of AVs. Case studies for re-design of existing facilities should be considered for rural, urban, and suburban facilities of local roads, signalized intersections, interchanges, and freeway and tollway systems. The research should assume that substantial fleets of AVs may be put into service quickly to provide specialized transit services in urban areas where the infrastructure has been suitably modified.

The research team will develop a guidebook of design considerations and key considerations and guidance for redesign of existing infrastructure to accommodate urban AV technologies that require some infrastructure protection. A blueprint work plan for future deployment activities to apply the strategies in several field test beds representing the range of facilities experienced in North American cities and regions will need to be developed.

Deliverables:

- Assessment of current roadway design tools like the Highway Safety Manual and the Highway Capacity Manual, along with tools like the Interactive Highway Safety Design Model (IHSDM)
- Four workshops on design principles for redesign of facilities in the context of AV operations
- Synthesis of recommendations for redesign and impacts to standards
- Research roadmap for future work to design and test principles in real-world scenarios

Resources:

Two-and-a –half person years, with expertise in roadway design and AV sensing and vehicle maneuvering capabilities. $500 K over 18 calendar months.

Urgency:

The workshops will help raise awareness of issues in the community; could be recommended as a Year 1-2 activity, or could follow research in signage, striping and other implementation of test-beds to gain some experience with what works and what doesn’t.

2.8 Cybersecurity Implications of CV/AV Technologies on State and Local Operating Agencies (1.2.4)

Research Problem Statement:
CV technologies and applications have significant security requirements, not only for the applications themselves, but also as potential access points that could enable attackers to get inside an agency's broader network and operations. Safety-critical messaging between vehicles and infrastructure (and vice-versa) needs to be trusted as being from a valid source and not spoofed by a hacker or malevolent agency. These cybersecurity requirements and technologies exceed the experience levels of most current DOT and local agency staff responsible for intelligent transportation equipment, as well as being more complex than most existing security schemes for commonly used services, such as online banking. Agencies need to understand the implications of these technologies on the design of their communications networks, networking equipment configuration, field device security, and operations best practices. AV technologies have similar vulnerabilities to hacking that could result in liability and public safety exposure to public agency owner/operators. While a proof of concept for SCMS has been demonstrated in the Safety Pilot and will be further evaluated in the DOT CV pilot deployment programs, the ultimate scalability of the security approach(es) will still need to be determined as the market penetration levels increase dramatically. The role of AASHTO and state and local agencies in the development of security standards and certification for AV/CV operation in a locality needs to be clearly identified.

Task Outline:
The research team will develop a primer on cybersecurity and related privacy issues in state DOT and local agency environments, based on experience gained in other domains where security and privacy issues are currently being managed (such as financial services). The report will focus initially on recommendations for best practices on a general level and then describe techniques that will support the agency in planning for the security environment and practices necessary for safety-critical CV applications, including the SCMS. The primer will provide recommendations for best practices and explore the development of standard requirements and testing and certification protocols for protecting the liability and burden of the protection of public safety for agencies when CV/AV technologies are in widespread deployment.

Deliverables:
- Phase I: Report on cybersecurity standards and best practices for CV applications
- Phase II: Analysis and recommendations on the role of AASHTO and state and local agencies in the development of cyber-security standards and privacy protections for AV systems

Resources:
Six person-months, with expertise on cyber-security in general and the cyber-security issues for CV systems in particular. $250 K over twelve calendar months.

Urgency:
There was strong interest in starting this during the first year so that the visibility of the security issues can be raised in time to influence work on the upcoming CV pilot deployments.

2.9 Workforce Capability Strategies for State and Local Agencies in Anticipation of Widespread Deployment of CV/AV Technologies (1.3.1, 1.3.9)

Problem Statement :
As intelligent transportation systems have become more and more commonplace over the last twenty years, state and local agencies responsible for transportation management and operations have typically developed a limited number of staff responsible for technology programs. With CV/AV technologies on the near horizon, operating agencies will have even higher demands for staff with technology experience, education, and training. This need will likely only increase as the market penetration level of the CV/AV technologies increases. Staff will be needed to make intelligent decisions on procurement, operations and management practices with respect to CV/AV systems. Duties of staff in certain roles such as transit vehicle drivers or snowplow operators will also become more technology-oriented as the lower-level driving function is phased out. Guidance is needed for agency decision-makers to transform their agencies into technology-savvy organizations that can attract a high-quality workforce.

Task Outline:
The research team will review existing literature related to long-term staff planning for DOTs and local operating agencies. The team will then summarize the current state-of-the-practice for agency staffing, program makeup, and training with respect to technology that is relevant to CV/AV systems at local, regional, and state levels. This initial step will likely involve some workshops with representatives of agencies that are innovators, implementers, and followers. Several organizational examples would then be used to identify strategies that an agency might implement to continually improve their readiness for the future world of automation. The report will provide recommended action plans and next steps for agencies.

Deliverables:
- Phase I: State of the practice summary white paper
- Phase II: Analysis and recommendations on workforce planning

Resources:
Six person-months, with expertise on transportation workforce issues. $150 K over 18 calendar months.

Urgency:
Almost all public agencies can’t “turn on a dime” and their makeup and organization evolve slowly. This project is not necessary to respond to “day one” applications. This task can run in parallel with several other efforts. Year 3-5.

2.10 State and Local Agency Data Management Strategies for CV/AV Applications (1.3.10, 2.1.1, 2.2.4)

Research Problem Statement:
As owners and operators of transportation infrastructure, state and local agencies maintain databases of relevant information. Currently, this includes crash records, design "as built" plan sets, traffic signal timing parameters, construction schedules, and many more. CV/AV applications need certain information about the environment and infrastructure in a variety of time scales. Signal timing status is obviously needed in real time, traffic sign placements might be updated daily, and the next month's construction projects might be updated weekly. Some AV developers are currently storing detailed digital 3-D maps for reference during automated driving. Perhaps such an asset of a public agency could be valuable to many applications, but this requires maintenance. Some agencies provide access to various sets of information electronically, others are available through records requests, and yet others are not available at all. Agencies vary widely in their ability to provide access to certain information now and in the future. There is a need to identify the information that is necessary for agencies to maintain to enable and enhance CV/AV applications, develop standard formats and standard systems where they would be helpful and do not already exist, and provide guidance for agencies on how to implement strategies for updating, maintaining, and disseminating the information.

Similarly, a variety of information about travel conditions can be collected by CV/AV enabled vehicles and can be shared with agencies to enhance their operations. Agencies currently struggle to collect good information about origin-destination flows, traffic volumes, travel delays, pavement surface quality, crash and anomaly location, and location of work zones, among others. There is a need to identify standards for collection of this information, how it is communicated to agencies, stored, maintained, updated, and eventually used to enhance transportation planning, operations and maintenance.

The Safety Pilot Model Deployment and the upcoming additional CV pilot deployments will continue to contribute valuable information on the design and implementation of management systems for dissemination of agency-owned data and ingestion of CV/AV generated information for agency operations. The scalability of these systems needs to be estimated in this research as the penetration level of CV/AV technology advances from several thousand vehicles to several millions. Similarly, each CV pilot deployment will only deploy a small subset of the 50+ envisioned applications. Scalability of the back-end system to eventually accommodate up to 50 applications will also need to be explored in this research.

Task Outline:
The research team will summarize CV and AV applications that require information from public agencies at various time scales and develop recommended strategies for agencies to update, maintain, and make this information available to CV/AV applications. The research team will review previous work such as the connected vehicle pooled fund study report on impacts of CV data on TMCs. Similarly, the research team will summarize CV and AV applications that can provide important information to public agencies at various time scales and develop recommended strategies for agencies to ingest, store and use this data. Scenarios for typical agencies at state, regional, and local levels will be developed as examples for data management

recommendations. A public sector task force will be established to provide feedback on project direction. The team will review existing standards, formats, and commonly used technologies and develop recommendations for harmonizing standards, developing dissemination and data collection systems or approaches, and approaches to maintaining the information that is disseminated and using the data that is collected over time. Maintenance of the information over time is the critical component of the research and the recommendations. This project should also identify data availability policies and methods to address privacy and security concerns while not compromising the value of the information collected from CV/AV enabled vehicles.

Deliverables:

- Phase I: White paper on state of the art in dissemination of agency information to the public and collection of information from AV/CV vehicles
- Phase II: Analysis and recommendations of data management strategies to meet typical agency needs

Resources:
Two person-years, with expertise on transportation agency data management and CV data categories. $500 K over 24 calendar months.

Urgency:
This project can and probably should follow the implementation of a few of the CV pilots and some AV application pilot projects at innovator agencies to see what worked and what needs revision for deployment at implementer agencies. This project would be a good candidate to coincide with the establishment of the CV deployment coalition. Year 4-5.

3 Planning Issues

3.1 Including Consideration of AV Systems in the Regional Transportation Planning Process and Tools (4.1.1, 4.1.5, 4.1.6)

Research Problem Statement:
Each potential future reality will need to be considered in long-range transportation plans. Freeway, arterial, and dense urban environments will all be affected by the advent of automated driving systems. In this vein, there is an urgent need for transportation planners to develop long-range transportation planning tools that take automated vehicle systems into consideration.

Existing regional planning and traffic assignment models (whether dynamic or static) assume that each person travels from place to place either using a personal vehicle or on a transit system. If a personal vehicle is used, the vehicle is assumed to remain parked at the destination until the traveler returns to the origin or begins a journey to their next destination (in “activity-based” variants of transportation planning models). Eventually, Level 5 fully-automated vehicles could offer additional options for vehicle ownership and operation, as they might be offered as a taxi-like service that would make other trips during the day. Millennials and future generations that have grown up with social networking technologies are showing markedly less interest in vehicle ownership, as they can remain connected to their friends and colleagues without physically being present.

In addition, AVs hold promise for increasing the capacity of existing transportation facilities if they rely on CV technology. By reducing the headways between vehicles and using communications to coordinate their behaviors, increases in highway capacity can be realized. Over time as the vehicle fleet approaches 100% automation, there is a potential to double current-day highway maximum throughput levels. V2V coordination of AVs can eliminate the traffic shock waves that travelers experience as “stop and go” driving.

Existing regional planning models in almost every incarnation predict that traffic will continue to rise as the population of an area rises. While it will likely continue to be true that *travel* necessarily rises as there are more people in a region, in the long term AVs may result in markedly less *traffic* if they can make shared-ride transit modes significantly more attractive. Millennials are already demonstrating the appetite for such with car-sharing services ranging from loaning their personal vehicles to others to shared-ride taxis. Roughly 70% of the cost of taxi services is devoted to the salary of the human driver; when this cost is removed through full automation, it stands to reason that such services will flourish.

Both increases in capacity and changes to traveler behavior due to automated vehicles need to be considered in long-range planning tools and processes, since we currently make major investment decisions encompassing billions of dollars of infrastructure based on travel demand predictions 30 years into the future. With CV technology likely to be mandated and intermediate levels of automation emerging within the next decade, infrastructure investments in transit lines, high-speed rail, and highway capacity improvements should be reassessed based on modeling of the likely impacts of CV/AV systems. Different types of investments may have higher societal payoff, such as re-design of urban centers or new types of intermodal facilities. In the longer term, the need for parking facilities and their locations may be changed significantly. These changes to land-use and urban planning tools are needed so that alternative future realities with automated vehicle services can be studied in a comprehensive manner. Considering the potential benefits to be gained from AVs, it is in our national interest to provide suitable tools and modeling systems that can assess the cost-benefit of various types of capacity and design changes.

Task Overview:
The research will identify the necessary components of the transportation network modeling process (on both the demand and supply sides) that need to change. The research team will form and engage an expert panel from transportation planning, modeling, and traveler behavior science. Sister processes including activity-based modeling, dynamic traffic assignment, and similar planning tools for inherently multi-modal systems will also need to reflect the influx of automated systems. Modeling theories will need to be developed and implemented in prototype, open-source tools that can be re-used by others and incorporated into existing commercial and publicly available systems. The research should characterize the key changes to each component of the transportation network modeling process and examine a number of potential alternative realities for several test locations. For example, tests might include predictions in several of the nation's major MPOs with different characteristics, including:

- Dense urban (e.g. Washington, D.C.)
- Sprawling suburban (e.g., Phoenix, AZ)
- Interurban (e.g. Dallas-Fort Worth, TX)
- Coastal (e.g. Los Angeles, CA)
- Low density (e.g., Boise, ID)

The research should identify how trade-off studies using the new tools will provide cost-benefit comparisons among different technological levels of automation, market penetration rates, and facility re-design. The research should assume that substantial fleets of AVs may be put into service quickly to provide specialized transit services in urban areas where the infrastructure has been suitably modified.

The products of this research will be theories and algorithms for considering AVs in the planning process, open-source software and tools for performing analysis, and the results from the example case studies. A blueprint work plan for future enhancements and opportunities for future collaboration among academia and transportation planners will be provided. Key guidance for MPOs and other planning organizations will be developed.

Deliverables:
- Synthesis of current state of the art in transportation planning and limitations for modeling AV systems
- Primer on relevant issues of automation for planners
- Methodology for incorporating AVs into existing tools or developing new tools as necessary
- Algorithms for planning and software implementation of tools
- Application results of tools on typical design scenarios
- Roadmap of future work and key additional research topics

Resources:
Five person years. $1.5 M over 24-36 calendar months.

Urgency:
Since this addresses long-term issues rather than present-day decisions, it can be started after the initial cluster of highest priority projects (Year 2 or 3).

3.2 Assessing the Transportation System Impacts of CV and AV Systems (original 2.4.3, 4.1.3, 4.1.4, 4.3.1, 4.3.2, 1.1.3)

Research Problem Statement:

Traditional transportation system design and planning models are not well equipped to assess the effects that CV and AV systems will have on transportation system operations, particularly in terms of traffic congestion, energy consumption and emissions. Representation of these effects requires enhancements to the existing models and careful application of the models to make sure that the effects of each technology are represented realistically and not over- or under-counted. These effects are strongly dependent on the market penetration of equipped vehicles and infrastructure, so modeling of the impacts also requires sensible predictions of the rate of growth of each market penetration and of the strategies that can be used to influence the distribution of equipped vehicles so that their drivers can be incentivized to operate them in close proximity to their peers, to the extent possible on the same portions of the roadway network. The strong interactions between the CV and AV technologies also need to be modeled accurately to represent the important distinctions between CV-only, AV-only and combined CV and AV operations.

Although the underlying models of transportation system impacts of the CV/AV applications will be developed under other projects (2.1), this project needs to make judicious choices of the input parameters to use in these models, accounting for significant uncertainties in the performance, timing, and market penetration growth of automation systems. Applying these models judiciously requires investment of substantial effort, but the knowledge gained from doing this work will provide essential inputs for a wide range of policy decisions that need to be made regarding support for deployment of systems.

Task Outline:

(1) Convene an expert panel to produce predictions of realistic ranges of the most uncertain parameters that will need to be chosen as inputs for many model runs (because they cannot be modeled directly), specifically of the market penetration growth rates of CV systems and of each level of AV systems and of the safety impacts that should be expected at each of these market penetration levels (individually and in combination).

(2) Apply the verified models to make predictions of the primary traffic, energy and environmental impacts of the CV and AV systems over the next 40 years in key representative scenarios. Choose which uncertain parameters to study using sensitivity studies over a range of credible parameter values. Conduct each assessment assuming both autonomous and cooperative automation systems so that the differences in impacts associated with cooperation can be understood as clearly as possible.

(3) Based on the results of model predictions, report at least on the following considerations:
   - Do the CV, AV or combined CV/AV systems produce sufficiently credible reductions in energy use or emissions that vehicles equipped with these systems could be given credit for these in a regulatory framework such as meeting national vehicle standards or for a cap-and-trade system?

- Are the benefits to traffic flow and delay reduction for the CV, AV or combined CV/AV systems sufficient to justify substantial public agency investments in their deployment and/or operation?
- How large are the additional benefits from connected automation compared to automation without connectivity (autonomous automation)?

Deliverables:

- Example results from use of the validated models that can help decision makers in general assign priorities for their support of various CV and/or AV applications.
- Recommendations regarding giving credit toward energy and/or emissions goals for CV and/or AV applications in meeting regulatory requirements.

Resources:

This is a large and challenging effort that is likely to require on the order of four to six labor years of effort during a period of two years. $1.5 M

Urgency:

High urgency to get started as early as possible after the modeling tools are developed in Projects 2.2 and 3.1, since the results will be needed by many stakeholders to support rational decisions about CV and AV deployment. It should therefore probably start in Year 3.

3.3 Effects of AV Systems and Technologies on Land Use, Travel Demand, and Traffic Impact Models (4.2, 4.2.1, 4.2.2, 4.2.3, 4.2.4, 4.2.5, 4.2.6, 4.2.7, 4.2.8, 4.2.9)

Research Problem Statement:
Existing regional land use and travel demand models assume that each person travels from place to place either using a personal vehicle or on a transit system based on a motivation such as going to work. Their choice of domicile is based on demographic factors, personal preferences, and their value of time. Fully automated vehicles offer additional options for vehicle ownership and operation as they might be offered as a taxi-like service that would make other trips during the day. Seniors and young children will find it easier to travel, potentially increasing VMT substantially. By presenting drivers today with additional options for their attention during travel, urban sprawl might accelerate. The need for parking and parking facilities could drop, or parking facilities can be relocated or re-imagined. Existing regional planning models in almost every incarnation predict that traffic will continue to rise as the population of an area rises and travel rates are predicted by the type of land use. In association with developments in regional planning models, higher-level land use and urban models will need to be modified as value of time and human behaviors change when AVs that change the driving experience substantially (SAE Level 3 or above) are commonplace. Different types of investments may have higher societal payoff, such as re-design of urban centers or new types of intermodal facilities. Real-estate developers will begin incorporating features for AVs that could change growth patterns. Traffic impact studies will change since existing trip generation rates and formulas will no longer be valid.

Task Overview:
The research team will summarize existing literature and document the current state of the art in land use and urban planning models. The research will identify the necessary components of land-use models that need to be modified to consider AV technologies. The research team will form and engage an expert panel from land use and urban planning. Modeling theories will be developed and implemented in prototype, open-source tools that can be re-used by others and incorporated into existing commercial and publicly available land use and urban planning modeling systems. The research should characterize the key changes to each component of the land use and locational selection modeling process and examine a number of potential alternative realities for several test locations. For example, tests could include predictions in several of the nation's major MPOs with different characteristics, including:

- Dense urban (e.g. Washington, D.C.)
- Sprawling suburban (e.g., Phoenix, AZ)
- Interurban (e.g. Dallas-Fort Worth, TX)
- Coastal (e.g. Los Angeles, CA)
- Low density (e.g., Boise, ID)

The research should identify how trade-off studies using the new tools will provide cost-benefit comparisons among different technological levels of automation, market penetration rates, and facility re-design. The research should assume that substantial fleets of AVs may be put into service quickly to provide specialized transit services in urban areas where the infrastructure has been suitably modified.

The products of this research will be theories and algorithms for considering AVs in the land-use planning process, open-source software and tools for performing analysis, and the results from the example case studies. A blueprint work plan for future enhancements and opportunities for future collaboration among academia and transportation planners will be provided. Key guidance for MPOs and other planning organizations will be developed.

Deliverables:

- Synthesis of current state of the art in land-use planning and limitations for modeling AV systems
- Primer on relevant impacts of automation for land use and urban planners
- Methodology for incorporating AVs into existing tools or developing new tools as necessary
- Algorithms for planning and software implementation of tools
- Roadmap of future work and key additional research topics

Resources:

Three person years. $1 M over 18 calendar months.

Urgency:

This project should follow the substantial completion of the project on modifications to macroscopic and mesoscopic regional transportation models to include representation of AV systems, which would put it into Year 4.

4 Modal Applications

4.1 Impacts of Transit System Regulations and Policies on CV/AV technology introduction (1.1.4, 2.2.11, 4.1.2)

Research Problem Statement:
CV/AV technologies offer potential benefits to improve safety and increase efficiency of transit systems for owners and operators. Closed, fixed-guideway transit systems could be re-imagined as lower cost services with rubber-tire vehicles that operate with less infrastructure protection. In addition, AV systems will impact transit services in qualitative ways. First- and last-mile AV services to bring riders to line-haul modes could significantly increase ridership. Dynamic taxi-like services could improve coverage of transit service to rural and suburban areas, however, relatively few state DOTs have significant involvement or influence over transit systems and there are many issues associated with transit operations that DOT and local agency staff need to better understand as CV/AV applications emerge. For example, extensive regulations and rules govern the operating parameters and characteristics of transit systems, some of which may be incompatible with CV and/or AV technologies, such as provisions to avoid elimination of current jobs regardless of the potential to create new jobs. The role of the driver will need to change, which will require significant coordination with labor unions. New procedures for certification of the safety of automated transit systems that are not confined to fixed guideways may be needed and insurance models for transit operators may need adjustment. These issues need to be better understood and next steps identified to enable widespread adoption of CV/AV technologies in transit systems.

Task Outline:
The research team will develop a primer on the regulatory and policy landscape of transit system planning, development, funding, and operations and identify the pain points or areas where any policy changes are necessary to accommodate (or facilitate) deployment of different types of CV/AV technologies. In particular, this project should explore how the existing procedures for certifying and testing fixed-guideway transit systems can be modified to apply to CV and AV systems that are not confined to fixed guideways. The team will then develop and deliver a set of recommendations and a plan of future work for adjusting the current regulatory and policy landscape of transit safety regulation.

Deliverables:
- Phase I: Report on existing transit regulatory/policy/operational environments and challenges for CV/AV technologies
- Phase II: Recommendations and plan of action for addressing the challenges

Resources:
Six person-months, $150 K over 12 calendar months.

Urgency:
Since this work is foundational for understanding work that needs to be done to facilitate CV/AV deployment in transit, it is a first year task. Experts in transit regulations and policies and fixed guideway system safety requirements are necessary for this study.

4.2 Critical Next Steps for AV/CV Applications in Long-Haul Freight Operations (1.1.5, 2.1.2, 2.2.5)

Research Problem Statement:
CV/AV technologies offer potential benefits to improve safety and increase efficiency of freight and goods movement in North America. The freight industry is extremely important to the economic vitality of our nation. Trucking is a strong component of this, as over 70% of all freight is carried by truck at some stage in the supply chain. The trucking industry faces critical challenges in maintaining adequate workforce. AV/CV technologies could be useful to fill in the unmet needs with automated resources, raise the status of a career in trucking, and reduce the workload of the driver in long-haul (and other) operations.

Truck parking and rest areas are currently strategically located to align with hours-of-service limitations. If hours-of-service were modified due to AV systems, national planning for rest areas and en-route facilities could be modified. Truck platooning is commonly identified as a near term application, but to make that a reality a variety of platooning protocols and procedures need to be defined and verified. Automated drayage and automated docking are frequently noted as highly desirable by the trucking industry. The regulatory, policy, and technical aspects of AV technologies on the trucking and freight operations industry need to be evaluated and recommendations developed for state DOT and local agencies that are involved with freight operations.

Task Outline:
The research team will review existing literature and develop a list of key issues and challenges in the regulatory, policy, and operations landscape of freight system operations and identify the pain points or areas where policy and operations strategy changes are necessary to accommodate (or facilitate) CV/AV deployment. In particular, truck platooning concepts should be explored and a list of near-term actions should be developed to answer the key research and policy questions.

Deliverables:
- Phase I: Report on existing freight regulatory/policy/operational environments and challenges for CV/AV technologies
- Phase II: Recommendations and plan of action for addressing the challenges

Resources:
Six person-months, with expertise in trucking operations and regulations and automation technology, $150 K over six to nine calendar months.

Urgency:
Since this work is foundational for understanding further work that needs to be done to facilitate CV/AV deployment in freight, it is a Year 1 task.

4.3 Benefit/Cost Analysis of Automated Transit System Concepts (1.1.4, 2.2.11, 4.1.2)

Research Problem Statement:

AV technologies offer potential to significantly improve efficiency of service for transit users. Automated systems could provide last-mile/first-mile type service or various concepts for circulation around activity centers. PRT and GRT systems that have been considered to be more efficient transit systems rely on dedicated guideway infrastructure that has resulted in unimpressive B/C estimates. Such systems could be re-imagined as rubber-tire technology for extensive point-to-point transit service systems on less protected infrastructure and deployed in the foreseeable future. Limited research is currently available that evaluates the impact of such services on small, medium, and large-scale implementation. This research will estimate the B/C performance of several types of automated transit concepts and compare their performance to future investments in traditional transit technologies (Light rail, BRT, heavy rail, etc.).

Task Outline:

The research team will first summarize the state of the art in transit automation, including the long history of PRT/GRT concepts and their evolution, with a focus on such transit systems' performance from a benefit/cost perspective. The team will then identify feasible automated transit concepts for demand-responsive transit, first mile/last mile transit access systems, and line haul transit systems with partial automation (lateral guidance, precision docking, automated platooning), evaluate their effectiveness, and estimate likely B/C performance. Simulation scenarios should be developed that can illustrate the performance efficiencies at several levels of deployment such as local, downtown circulators, regional (enhanced service to rural or suburban areas underserved by current transit), and mega-regional. Incremental levels of automation should also be considered where operators (or "customer service agents") are still present in each vehicle. The assessment will identify where automated transit systems are a best fit for improving mobility and level of service to transit patrons. The team will then summarize the findings and recommendations for the best plan of action towards implementation of pilot projects to demonstrate feasibility of the most effective concepts from a B/C perspective.

Deliverables:

- Phase I: Deployment concept scenarios
- Phase II: Analysis results and conclusions

Resources:

Two person-years, with expertise in transit operations, benefit-cost assessment and automation technologies, $500 K over 18 calendar months.

Urgency:

This work could be pursued in parallel with the research on policy impacts, or could follow the completion of the transit policy study. Year 1 or 2 task. Automated transit systems in controlled environments such as campuses represent potential "low hanging fruit" for AV progress such as demonstrated by the CityMobil2 project in Europe.