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

Interim Deliverable

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Summary

This interim report provides policy and planning strategies at the state, regional, or local levels that, if implemented, could help internalize the societal impacts of automated vehicle (AV) and connected vehicle (CV) technologies in market decisions made by consumers and producers. *Why would these governments want to do this?* State, regional, and local governments always seek to ensure the safe and efficient operation of public roadways; overseeing AV and CV technologies is a natural extension of this longstanding mission.

Vehicles that are increasingly automated and connected have the potential to change personal, freight, and public transportation profoundly. The potential benefits to society are immense. As producers sell AVs and CVs and consumers buy them, crashes, traffic congestion, air pollution, and other negative externalities associated with driving may significantly diminish. On the other hand, AVs and CVs may have drawbacks and pose risks. Technology will solve some problems but could also create new ones. For example, cybersecurity vulnerabilities associated with CVs could compromise safety. Congestion could increase with the proliferation of AVs as driving becomes less onerous and individuals without driver licenses have more opportunities for travel.

Many of the benefits and drawbacks will be felt by third parties, who are not involved in the market of selling and buying AVs and CVs. One of the fundamental concepts in economics is that people buy and sell goods and services from each other for their mutual benefit. However, it is often the case that the two parties engaged in an economic transaction are not the only ones affected by it. While some market mechanisms force one or both parties to consider these effects, there are many cases in which neither party has to deal with the consequences of their actions. The third-party effects are *externalities*. An externality is an effect produced by either a consumer or producer that affects others yet is not accounted for in the market price (i.e., occurs external to the market).

Society as a whole could benefit if state, regional, and local governments were to implement policy instruments (e.g., regulations or taxes) or planning activities (e.g., public education) to internalize these externalities in decision making by consumers or producers. Such instruments or activities could force the market to account for costs that would otherwise not be included.

Externalities of AVs and CVs

The analytical foundation for identifying potential policy instruments and planning activities was an examination of the role of AVs and CVs in mitigating or exacerbating existing transportation externalities. This summary presents a brief introduction to existing transportation externalities below. Chapter 3 in this report is devoted to discussing the effects of AVs and CVs on the externalities. Also, there are in-depth treatments provided in the briefing papers in the appendices.

- **Traffic crashes:** When individuals drive a vehicle, they not only increase their own risk of a crash and its associated costs, they also increase crash risks and costs for other

motorists, pedestrians, cyclists, and society in general. Vehicle-to-vehicle (V2V) safety applications could mitigate this externality by addressing a majority of vehicle crash types if the V2V applications are demonstrably effective and widely used, and the driver-vehicle interface performs well. A marginal increase in benefit could be obtained through vehicle-to-infrastructure (V2I) safety applications depending upon V2I extent. Even without CVs, AVs could reduce a majority of driver-related errors, which account for a vast majority of traffic crashes, but they also might introduce new types of errors.

- **Congestion:** As the number of vehicles on a road increases past a certain density, vehicle speed and throughput decrease, causing congestion. Each additional driver adds to the congestion of other drivers but does not bear the full cost of that effect. Ultimately, it is unclear how AVs and CVs will affect congestion: the literature in this area has found mixed results for a variety of different traffic measures under varying conditions. CV applications could mitigate congestion by reducing delays caused by safety incidents and by increasing system efficiency. These impacts would be maximized if there were widespread adoption of V2V capabilities, widespread V2I infrastructure, and interoperability among mobility applications. AVs that are safer than human drivers could enable the reduction of crash-related delays. At the same time, a proliferation of on-demand AVs could put more vehicles on the road and increase congestion. Although the travel delay caused by congestion may be redefined if the occupant in an AV is enabled to be productive while waiting in traffic, there still might be the need to minimize associated vehicle miles traveled (VMT) growth because it contributes to other externalities.
- **Pollution:** Vehicles emit local air pollutants (e.g., particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide) and global air pollutants (greenhouse gases). When someone drives a vehicle, he or she reduces the air quality and adds to noise pollution in surrounding areas. That person also imposes the costs of climate change on the global society. AVs could mitigate this externality by leading to reduced vehicle production rates and parking needs, and to increased use of smaller, electric vehicles and eco-driving. AVs and CVs could also increase this externality by increasing safety and improving the convenience of vehicle travel, lowering transportation costs. While the associated increased VMT may facilitate additional economic activity or enhanced quality of life, the increased VMT may bring negative environmental impacts that would need to be mitigated.
- **Land development:** Land devoted to automobile infrastructure and to inefficient development patterns, while historically increasing mobility and decreasing travel costs, may also pose negative environmental, economic, and public health effects on society. As noted previously, AVs and CVs could increase safety, improve convenience of vehicle travel, and lower transportation costs. These effects might lead consumers to take more trips and travel more miles in order to access lower priced land and rural locations, exacerbating the negative effects. On the other hand, if fully autonomous (Society of Automotive Engineers Level 5) AVs reduced the need for parking adjacent to destinations, land dedicated to parking in urban areas could be reused for other uses

that provide greater benefit to society. The largest effects would be in dense urban areas, where land is very expensive. Thus, the impacts might not be substantive in most areas of the country.

- **Mobility:** Older adults, youths under age 16, and individuals with disabilities have limited access to desired destinations, activities, and services, which can be viewed as a negative externality of the existing transportation system. Level 5 AVs may offer a reduction of the existing negative externality by enabling significant improvements in access and mobility for such individuals. This is particularly true for those who live in areas with few alternative modes. The benefits of less-than-full automation (Level 3 and Level 4) and CVs in reducing this negative externality are unclear, however.

AVs and CVs may also result in a range of economic disruptions to groups such as professional drivers, insurance companies, medical facilities, trauma centers, body shops, and other industries. Some of these effects are internal to the market, while others are pecuniary externalities (i.e., operating through market prices) and not real externalities. Because these costs are internal to market decision making, the authors have excluded economic distruptions from the analysis.

The report presents detailed information from both a literature review and analysis to address five questions related to the five existing transportation externalities:

- What is the externality?
- How significant is it?
- What factors contribute to the externality?
- How could CVs and AVs lead to *socially desirable* outcomes regarding it?
- What actions of producers and consumers would enable these desirable outcomes but might not be taken because the societal impacts are external to their decision making?

A synthesis of answers to the last question served as a bridge to the identification of policy instruments and planning activities at the state, regional, or local levels that could be used to internalize the externalities of AVs and CVs in the market decisions of consumers and producers. The research team focused on decisions (manifested as *actions* of consumers and producers) that would enable *desirable* outcomes of AVs and CVs. The reasoning was that this would serve to align public-sector and private-sector interests. These actions are presented in Tables ES-1 and ES-2. The *actions* in these two tables are not assumptions but desired outcomes (i.e., beneficial to society).

Table ES-1. Actions of Consumers and Producers Enabling Desirable Outcomes of CV Technology.

	Enabling Actions Pertaining to CV Technology
Consumers	**Consumers purchase CVs with…**
	Safety applications
	Mobility applications
	Environmental applications
	Consumers actively and attentively use CV…
	Safety applications
	Mobility applications
	Environmental applications
Producers	**Producers develop and sell CVs with interoperable…**
	Safety applications
	Mobility applications
	Environmental applications

Table ES-2. Actions of Consumers and Producers Enabling Desirable Outcomes of AV Technology.

	Enabling Actions Pertaining to AV Technology
Consumers	**Consumers purchase AVs…**
	That are safe
	That drive smoothly and avoid harsh braking and acceleration
	That are smaller, lower polluting, or electric
	With eco-driving operating objectives
	Consumers use...
	AVs safely in accordance with maintenance and operating procedures
	AVs but, despite lower travel costs, do not drive further for housing
	Level 5 AVs to avoid parking in urban centers
	Shared AVs rather than private AVs
	Aging adults, youths under age 16, or disabled consumers…
	Purchase Level 5 AVs
	Use Level 5 paratransit or shared services
Producers	
OEMs	**Producers develop and sell AVs...**
	That are smaller, lower polluting, or electric
	That drive smoothly and avoid harsh braking and acceleration
	With eco-driving operating objectives
	That are Level 5 vehicles and are usable by aging adults and individuals with disabilities
	At a price that is affordable for private ownership or shared services
	And at the same time, act on communications with road operators about infrastructure/maintenance necessary to ensure safe and efficient operations of Level 4 and Level 5 vehicles (across different use cases/operating conditions)
Developers	Developers build fewer parking facilities or build parking facilities that can be adapted to other purposes.
Shared services	**Private shared-vehicle ownership, services, transit, or paratransit...**
	Purchase and operate shared AVs
	Purchase Level 5 vehicles and operate them at affordable prices
	Prioritize ridesharing and linkages with line-haul mass transit

Impacts on Transportation Agencies

Societal benefits from AV or CV technologies may be maximized through the actions (decisions) of producers and consumers as indicated in these tables. However, the impact of these actions on state and local transportation agencies is uncertain. The research team identified potential areas of impact to transportation agencies into three different categories of impacts:

- **Institutional:** Institutional impacts affect a transportation agency's focus, areas of authority, and/or organizational structure. This includes how an agency prioritizes its responsibilities and chooses to allocate its funding. Proliferation of AVs and CVs could increase transportation agencies' focus on non-safety goals; increase responsibility for data integrity, security, privacy, and analytics; and increase reliance on outsourcing to the private sector.
- **Operational:** These are impacts on how an agency develops, maintains, operates, and manages transportation infrastructure and transportation-related services. Proliferation of AV and CV technologies could cause existing intelligent transportation system investments to become outdated, could reduce or shift demand for transit and parking services, and could increase maintenance requirements. It is uncertain whether the technologies will mitigate or exacerbate current deficits in available roadway capacity.
- **Funding and financing**: These are impacts to the funding and financing sources available for transportation infrastructure and related services. AV and CV systems could exacerbate funding deficits through increased costs for maintaining and operating roadways. A proliferation of shared AVs could reduce the amount of revenue from driver licensing, vehicle sales tax, vehicle registration, moving violations, transit fares, and federal funding associated with ridership levels. CV technology could potentially increase revenue from road user charges.

It is critical that recommended policy instruments and planning activities are mindful of these potential impacts to transportation agencies.

Policy Instruments and Planning Activities

Through literature review and analysis, the research team compiled and organized a list of potential policy instruments and planning activities that state, regional, and local governments could use to internalize externalities in road transport, generally. The team then assessed these against each externality action in Tables ES-1 and ES-2 to identify policy instruments and planning activities that could enable desirable societal outcomes. Four categories of policy instruments were identified as being particularly effective at internalizing externalities:

- **Taxes, fees, and subsidies:** By directly changing prices, these policy levers intend to take the harm that an actor imposes on society and apply a tax, fee, or subsidy on the source of the harm, equal to the magnitude of harm. These are collectively discussed as economic instruments in this report.

- **Regulations:** Command-and-control instruments require firms or individuals to restrict or increase the supply of a good or to comply with specific standards, such as technology or performance standards.

This analysis also identified four categories of planning and other activities that a transportation agency might undertake to achieve the same outcomes. These included:

- **Structure of private rights**: An agency may restructure civil and criminal liabilities in order to shift risk and alter producer and/or consumer behavior.
- **Service provision**: An agency may change how it provides its current range of transportation services. Or, an agency might make changes in transit operations to accommodate new user groups.
- **Information/education**: An agency may orchestrate a public information campaign targeting various groups for general advisement, encouraging desired behaviors, and discouraging undesirable behaviors.
- **Financing/contracting/collaboration**: An agency may establish a transportation market itself or in partnership with the private sector when a private-sector market does not exist or cannot exist without government intervention.

In total, the team identified more than 200 potential policy and planning strategies at the state, regional, or local levels that, if implemented, could help internalize the societal impacts of AV and CV technologies in market decisions made by consumers and producers. These strategies are reviewed in Chapter 4 of the report.

Recommended for Further Study

The team culled the 200+ candidate strategies and selected 12 policy instruments and planning activities for which detailed assessments would be conducted, using two questions:

1. What strategies fall within the general purview of state, regional, and local agencies?
2. What strategies have the greatest near-term applicability?

These 12 strategies are summarized in Table ES-3.

Table ES-3. Recommended Policy and Planning Strategies for In-Depth Assessment.

Type	Category	Policy/Planning Strategy
Economic	Taxes	1. Apply road pricing, including tolling, parking pricing, and emerging applications of distance-based pricing, to minimize VMT growth
	Subsidies	2. Accelerate CV market penetration by subsidizing equipped vehicles, both original equipment and after-market retrofit of conventional vehicles
	Subsidies	3. Subsidize shared-vehicle services to minimize VMT growth, increase vehicle occupancy, and support ridesharing and transit services, including paratransit
	Subsidies	4. Create economic incentives, such as pre-tax transit benefits and location-efficient mortgages, to support market penetration of shared AVs near transit nodes, urban centers, and commercial centers
Regulatory/ Planning	Obligations for operator behavior	5. Establish, codify, and enforce CV and AV operator/owner/passenger requirements, including training, and making installation and use of applications a component of driver training and licensing
	Structure of private rights	6. Restructure liability regimes, including insurance requirements, to accelerate market penetration
	Structure of private rights	7. Implement land use regulations and parking requirements to increase density in support of market penetration of shared AVs at transit nodes, urban centers, and commercial centers
	Structure of private rights	8. Enact legislation to stimulate CV or AV testing
	Service provision	9. Invest in CV infrastructure in collaboration with the private sector
	Service provision	10. Grant AVs and CVs, including transit, shared, and commercial vehicles, privileged access or services (high-occupancy vehicle/managed lanes, signal priority, and parking access)
	Information	11. Increase public awareness through education, training, communication, and outreach to stimulate consumer action and supportive public investment
	Financing/ contracting	12. Implement new contractual mechanisms with private service providers, including shared data arrangements

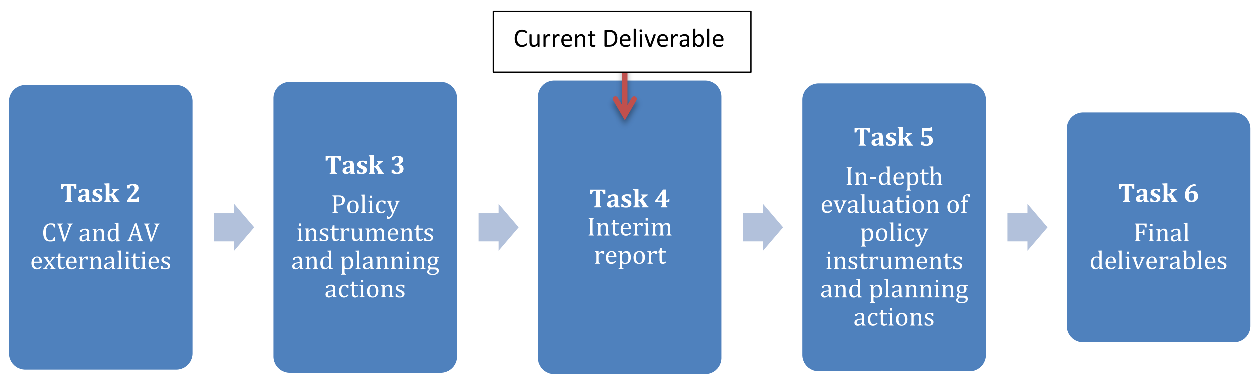
Following the acceptance of this Interim Report by the National Cooperative Highway Research Program and the project oversight panel, the research team will conduct in-depth assessments, in the form of topically oriented white papers, which will evaluate the feasibility and viability of the 12 policy or planning strategies for the intended purposes.

1. Introduction

Study Objective

Vehicles that are increasingly automated and connected could offer many benefits to society in areas such as safety, mobility, and environmental sustainability. However, they may also pose risks and drawbacks through cybersecurity vulnerabilities that compromise safety. Many of the benefits and drawbacks will be felt by third parties who are not involved in the actual production or use of autonomous vehicles (AVs) and connected vehicles (CVs). These third-party effects are *externalities* of AVs and CVs, and society as a whole would benefit from the internalization of these externalities into private-sector decision making.

The objective of this research, as stated in the request for proposals, is "to identify and describe policy and planning actions at the state, regional, and local levels that could help societal impacts (including impacts on transportation system owner/operators) of CV and AV technologies to be internalized in market decisions made by individuals and organizations." The final deliverable of the research will include a menu of policy and planning actions at the state, regional, and local levels that could be used for this purpose. Figure 1 shows how Tasks 2–6 in this project will lead to these outcomes. This interim report represents the Task 4 activity and covers the results of Task 2 and Task 3.



Note: Task 1 is the study management.

Figure 1. Study Tasks.

In Task 2, the research team examined the externalities of CVs and AVs. This work identified the externalities of driving, and for each externality, the research identified:

- Factors that contribute to the externality.
- Positive societal impacts of CVs and AVs.
- Actions of producers and consumers of CVs and AVs that might enable positive outcomes for society but might not be taken because societal benefits are external to their decisions.

The information is summarized in the body of this report. Detailed information is found in briefing papers for each externality in the appendices. This information created knowledge that the research team used in Task 3 to identify appropriate candidate policy instruments and planning actions. In Task 3, the research team examined:

- Policy instruments to internalize externalities.
- Planning activities that may be deployed in response to externalities arising from AV/CV implementation.
- Specific alignments of policy instrument and planning activities to actions of producers and consumers.

The team will use the results of Tasks 2 and 3 in performing Task 5, in which the team will evaluate the feasibility, applicability, and impacts of candidate policy instruments and planning activities in depth. To clarify the Task 2 and Task 3 results, the authors begin this report by defining the scope of the study.

Scope of the Research

To ensure a common understanding of the research direction and ultimate results, the study team defines the scope of the study in terms of three main points:

- Definitions of AVs and CVs.
- Externalities of interest.
- Relevant actors.

Definitions of AVs and CVs

For the purposes of this work, AVs are vehicles that take full control of all aspects of the dynamic driving task for at least some of the time. Society of Automotive Engineers (SAE) International's J3016 describes six levels of increasing autonomy that may be possible in vehicles, as shown in Table 1. Using SAE's taxonomy, *this National Cooperative Highway Research Program research focuses on the role of Level 3–5 AVs in mitigating or exacerbating the externalities of driving,* or in creating new externalities.

A connected car (CV) has internal devices that connect to other vehicles, as in vehicle-to-vehicle (V2V) communication, or a back-end infrastructure system, as in vehicle-to-infrastructure (V2I) communication. V2V applications enable crash prevention, and V2I applications enable telecommunication, safety, mobility, and environment benefits. Their foundation is data communications that enable real-time driver advisories and warnings of imminent threats and hazards on the roadway (Hong et al. 2014). Dedicated short-range communications standards—two-way, short-to-medium-range wireless communications capability that permits very high data transmission—are currently the leading medium for V2I safety applications (e.g., red light violation warnings, curve speed warnings, and work zone warnings) and V2V safety applications (e.g., forward collision warning, intersection movement assist, left-turn assist, and do not pass warning). However, non-safety critical applications (e.g., weather advisories and eco-approach and departure at signalized intersections) could also be achieved using wireless communication. At present, the V2I and V2V applications solely provide driver alerts; they do not control the vehicle operations.

Table 1. Levels of Driving Automation (SAE 2014).

Level	Name	Description
Human driver monitors the driving environment		
0	No automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems
1	Driver assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task
2	Partial automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task
Automated driving system monitors the driving environment		
3	Conditional automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene
4	High automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene
5	Full automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver

Externalities of Interest

Vehicle automation and connectivity have the potential to transform the transportation system and in doing so affect how we live—such as our public health, economic growth, land use, and environmental sustainability. Some of these effects may result in externalities.

An externality is an effect that one party imposes on another party without compensating them for the effect if it is negative, or charging them for it if it is positive (Buchanan and Stubblewine 1962). Two examples of externalities, one negative and one positive, are as follows:

- **Pollution:** A common example of a negative externality is pollution. For example, a steel-producing company might create air pollution. While the firm has to pay for the energy and raw materials used in the production process, the individuals living near the factory will pay for the pollution in the form of higher medical expenses, poorer quality of life, reduced property values, and so forth. Specifically, pollution of carbon dioxide and methane creates a significant negative externality on a global scale by increasing greenhouse gases in the atmosphere.
- **Vaccines:** Vaccines are a good example of a positive externality because they have benefit for society as a whole. Once a critical portion of a community is immunized, the community as a whole is protected because there is little opportunity for an outbreak to

take root. Those who cannot receive immunizations (e.g., due to compromised immune systems) are protected from infection through human-to-human transmission by community or herdimmunity. However, an individual may only consider the marginal private benefit and the marginal private cost when determining whether or not to get immunized (Boulier et al. 2007).

This study focuses on the externalities of CVs and AVs. Many of the CV and AV externalities will be changes to an existing transportation externality, rather than an entirely new externality. Congestion, for example, is an existing externality of driving that AVs could affect. When drivers enter a road space, they receive some benefit (the mobility provided by the road) and face some cost (the expense of driving, including time cost). What drivers do not have to bear are the costs of delays they create for other drivers on the road as well as public health and environmental impacts upon communities in the proximity of congestion (Centre for Economics and Business Research 2014, Parry et al. 2007). Since those costs are external to an individual's decision to drive, roads can become congested due to higher demand than is supported by infrastructure. Suppose, however, that AVs were more efficient than traditional vehicles—reducing the sharp acceleration and braking that contributes to congestion and perhaps decreasing the required safe following distance between vehicles (due to faster and/or coordinated reactions time among AVs through connectivity). Users of AVs, under this assumption, would increase roadway efficiency and reduce congestion not only for themselves, but for all other road users (all other things being equal). This would have positive effects on public health, the economy, and the environment.

Unfortunately, many negative externalities also arise from driving. In Task 2, the study team reviewed existing literature to identify and characterize the primary externalities associated with traditional (non-AV and non-CV) driving (Small and Kazimi 1995, Delucchi 2000, Parry et al. 2007, Michalek et al. 2011). This report identifies these as:

- Congestion.
- Traffic crashes.
- Opportunity cost of land.
- Local and global air pollution.
- Foreign oil dependence (examination of the foreign oil dependence externality has not been included in the analysis because of its far-reaching geo-political externalities).
- Noise pollution.
- Reduced mobility and access to desired destinations for the elderly, youths under age 16, and individuals with disabilities that results from the car-centered transportation system.

The analysis then examined the role of AVs and CVs in mitigating or exacerbating these externalities.

In addition, AVs and CVs may result in a range of economic disruption, such as to professional drivers (e.g., taxis, long-haul trucking, and limo services) and to insurance companies, medical facilities, trauma centers, body shops, and an entire crash economy (Anderson et al. 2014). Some of these effects are internal to the market, while others are pecuniary externalities and not real externalities. As a result, the authors exclude them from the analysis.

Table 2 lists the externalities examined in this study, explains them, and notes areas of societal impact.

AVs and CVs may have positive and negative effects on society. Society benefits the most when the positive effects are maximized and the negative effects are minimized. However, if these effects are external to the decisions that AV/CV producers and consumers make, their private actions may not align with societal goals. Society would be less well off than would be possible if the effects were internalized.

One justification for governmental interference in markets is the existence of externalities. Social welfare can be increased if these externalities are internalized so that the costs faced by individual actors represent the social costs of their actions (including the externalities). It is, therefore, a function of governments to internalize (or cause to be internalized) the externality. For example, some governments require polluters to pay a tax or obtain permits in the market for emitting pollutants, thus helping make the cost of pollution internal to the decision to pollute (Environmental Protection Agency 2015). In the case of congestion, a congestion toll can be levied (Parry et al. 2006). In the case of the positive externality created by vaccines, the government subsidizes vaccinations to decrease the individual cost, thereby increasing the individual demand for vaccines and maximizing social benefits (Hinman et al. 2004). Many states require children to receive vaccinations in order to attend school. This creates a cost to *not* obtain vaccinations (e.g., parents who do not wish to vaccinate their children may have to homeschool them) (Bugenske et al. 2012).

Table 2. Externalities Examined in This Study.

Externality	Explanation of Externality	Areas of Societal Impact
Traffic crashes	Crash externalities occur because when someone drives a vehicle above those costs not internalized by insurance payments, they not only increase their own risk of a crash, but also the risk to other road users—including pedestrians and bicyclists. The cost components include productivity losses, property damage, medical costs, rehabilitation costs, congestion costs, legal and court costs, emergency services, insurance administration costs, and the costs to employers. Values are sometimes also put on intangibles such as physical pain or loss of quality of life. Thus, crashes pose a huge public health and economic cost to society.	Public health, economic development
Congestion	As the number of vehicles on a road increases past a certain density, vehicle speed and throughput decrease, causing congestion. When a driver uses a busy road, he or she adds to congestion that other drivers experience but does not have to pay for the cost of that congestion—the lost productivity of other drivers as they sit in traffic, the delay in goods and resource movement, and the increase in pollution around areas of congestion. Congestion poses a large economic and public health cost to society.	Public health, economic development, environmental sustainability
Land development	Driving requires roads and parking, and much land is used to provide infrastructure for vehicles. There is an opportunity cost associated with this infrastructure—it is space that could otherwise be used for homes, parks, businesses, and other facilities. Drivers impose this opportunity cost of land on society, with environmental, economic, and public health effects (Delucchi and Murphy 2008, Litman 1997).	Public health, economic development, environmental sustainability
Local and global air pollution	Automobiles emit local air pollutants (e.g., particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide) and global air pollutants (greenhouse gases) when they combust fuels, primarily fossil fuels. Thus when people drive vehicles, they reduce the air quality of those in the surrounding area and impose the costs of climate change—a global effect—on everyone. These pollutants impose public health, environment, and economic costs on society, locally and globally (Colvile et al. 2001, Krzyżanowski et al. 2005).	Public health, economic development, environmental sustainability
Noise pollution	Driving can be loud. There is noise from engines, the contact between wheels and the road, braking, and honking. When people drive, they add to the noise pollution of those who live and work in the area. Noise pollution has impacts on public health and economic development (Delucchi and Hsu 1998).	Public health, economic development
Reduced mobility for aging adults, individuals with disabilities, and others	Aging adults and individuals with disabilities often have significant mobility and access limitations. They may be unable to drive, and the alternatives available to them may be limited, costly, and difficult to use. The lack of mobility and access to desired destinations, activities, and services can lead to social isolation and a host of negative consequences for them and for society.	Public health, equity, mobility

Relevant Actors

In Task 3, this study analyzed potential policy instruments and planning actions that could be used to internalize societal benefits in private-sector decisions. The private-sector actors that are of interest are producers and consumers of AV and CV technologies:

- Producers include automobile manufacturers, technology firms, and Tier 1 suppliers (i.e., Tier 1 companies are direct suppliers of parts to automobile manufacturers). (The U.S. Department of Transportation [USDOT] and university research institutions are also producers of CV technology but not relevant actors for this study because of the study's focus on private-sector actors.)
- Consumers include private individuals and private-sector fleet owner/operators.

In addition, the study is concerned with the state and local transportation agency perspective in two ways:

- Determining the impacts that AVs and CVs might have on these agencies.
- Identifying actions that state, regional, and local agencies could take to internalize externalities or cause producers/consumers to internalize externalities.

On the other hand, policy instruments or planning activities that might be initiated by federal agencies, such as the National Highway Traffic Safety Administration (NHTSA) cannot be undertaken by state agencies. In Task 5, the research team will further evaluate policy instruments and planning activities to assess their efficacy and aptness for the intended audience.

Report Organization

After this introduction, the report is organized into the following sections:

- **Chapter 2: A** synthesis of externalities of AVs and CVs
- **Chapter 3:** Summary discussions of the externalities of AVs and CVs, taken from in-depth treatments of each externality.
- **Chapter 4:** Analysis of state, regional, and local policy instruments and planning actions that could be used to internalize the externalities of AVs and CVs.
- **Chapter 5:** Suggestions on which categories of policies or planning warrant in-depth evaluation.
- **Appendices:** Five briefing papers that examine the impacts of CVs and AVs on the existing transportation externalities.

2. Synthesis of Externalities of CVs and AVs

Task 2 Analytical Approach

The end goal for Task 2 was to identify actions that AV and CV producers and consumers could take to increase social welfare but might not take because the social welfare impacts are external to their decision. These actions include ones that would have direct positive effects on society. For example, it would benefit society if producers create AVs that are safer than conventional autos, thereby reducing crashes and congestion. However, producers might not market AVs, even if they are safer, out of concern for greater liability when the inevitable crash occurs if the liability rule does not incorporate the benefits of AVs. Producers' actions might be different if the societal benefits were part of the liability calculus.

Actions may also include ones to avoid negative externalities. For example, if AVs reduce the cost of time spent in a car, their owners may take more and longer trips, thereby adding to congestion. It might increase social welfare if, instead, owners of AVs minimized their vehicle miles traveled (VMT) growth because the societal cost of the additional driving was included in their decision. Both of these actions—producing safer AVs and minimizing VMT growth—are inputs into Task 3 because they are candidates for policy and planning interventions to internalize their societal effects.

Researchers identified these candidate actions in two steps.

1. Identified ways in which AVs and CVs could have positive outcomes for society—either by having direct positive effects (e.g., if safer, AVs would reduce crashes and congestion) or by avoiding negative ones (e.g., AVs do not encourage more driving even if they reduce the cost of driving).
2. Identified the private-sector actions that could help to bring about these positive outcomes but that might not be taken because the positive outcomes are not fully internalized in the private sector's decision making (again, producers making and marketing safer AVs and consumers not driving more).

Researchers are not quantifying, projecting, or developing scenarios of AVs and their external effects; rather, they are identifying mechanisms through which externalities may occur and finding mechanisms and actions that would lead to positive outcomes and avoid negative ones.

There are many diverse AV and CV capabilities, each of which may present different externalities. For example, an SAE Level 5 vehicle (which drives itself all of the time without human intervention) may offer the positive externality of improving mobility for the elderly and disabled, but an SAE Level 3 vehicle (which requires human intervention) cannot offer this benefit. Thus, in the analysis, researchers identified the target actions in each major technology category—V2V, V2I, Level 3 AV, Level 4 AV, and Level 5 AV—where applicable.

The research team examined each of the externalities with the two-step approach. The results are presented in in-depth briefing papers in the appendices. The rest of this section summarizes these results and concludes with a discussion of how the outcomes and actions may affect state and local transportation agencies.

How CVs and AVs Could Lead to Positive Societal Outcomes

By what mechanisms might AVs and CVs *create desirable outcomes for society, either by encouraging direct positive effects or reducing negative ones*? Through inferences based on reviews of the literature, the research team identified ways in which CVs and AVs could lead to desirable outcomes for society. These are discussed generally for each externality; greater detail can be found in the summaries presented in the next chapter and the briefing papers in the appendices.

Traffic Crashes

When individuals drive a vehicle, they not only increase their own risk of a crash and its costs, they also increase crash risks and costs for other motorists, as well as pedestrians, cyclists, and society in general. V2V safety applications can mitigate this externality by addressing a majority of vehicle crash types if the V2V communication is successfully interpreted and acted upon (Najm et al. 2010). This outcome necessitates that CV applications are demonstrably effective and widely used and that the driver-vehicle interface performs well. A marginal increase in benefit can be obtained through V2I safety applications, depending upon the extent to which V2I infrastructure exists widely (Eccles et al. 2012). Even without V2V, AVs can reduce a majority of driver-related errors, which account for 94 percent of traffic crashes according to NHTSA (2015a). To achieve this outcome, certain mechanisms need to be in place. SAE Level 3 vehicles in which the human driver is still in the loop should only be deployed after having been demonstrated to be safe due to evidence of human driver performance gaps. Level 4 and Level 5 AVs will need to alleviate driver-related errors across a wide range of operating conditions, not just under specific conditions, such as highway driving in light traffic. Safeguards and fail-safe systems are necessary so that AVs will not introduce new types of vehicle errors (i.e., cybersecurity risks) because of their reliance on advanced computing and digital systems.

Congestion

As the number of vehicles on a road increases past a certain density, vehicle speed and throughput decrease, causing congestion. Each additional driver that takes to the road adds to the congestion that all drivers bear, although each motorist does not bear the full cost of his or her decision to drive. They pay for the costs they incur directly but not for the costs they impose on society, such as additional delay, environmental harms, and wasted fuel. Congestion occurs on a regular basis (i.e., recurring) and is sporadically due to accidents, construction, weather, and so forth (i.e., non-recurring). CV safety applications could mitigate non-recurring congestion events by reducing delays caused by safety incidents through informing CVs of the delay, enabling them to choose a different route. CV mobility applications could positively impact recurring congestion by increasing system efficiency. These impacts would be maximized if there were widespread adoption of V2V capabilities, widespread V2I infrastructure, and interoperability among mobility applications. AVs that are safer than human drivers would enable the reduction of crash-related delays. AVs that operate with more precision and control than human drivers could plausibly enable infrastructure operators to redesign aspects of their facilities to accommodate more traffic (e.g., narrower lanes and shorter headways), thereby increasing supply. AVs and CVs could affect congestion in potentially negative ways as well by inducing travel demand.

Pollution

Automobiles emit local air pollutants (e.g., particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide) and global air pollutants (greenhouse gases) when they combust fuels, primarily fossil fuels. Thus when someone drives a vehicle, they reduce the air quality of those in the surrounding area and impose the costs of climate change—a global effect—on everyone. Vehicles are also loud. When people drive, they add to the noise pollution of those who live and work in the area. Noise and air pollution are due to vehicle factors (e.g., type of vehicle), travel factors (e.g., number of trips), driver behavior (e.g., driving style), and infrastructure (e.g., operation of transportation infrastructure).

AVs and CVs have the possibility to affect each of these categories. In terms of vehicle factors, AVs could lead to changes in vehicle production rates, reduced parking needs, use of right-sized vehicles, and improved environmental outcomes. In terms of travel, AVs and CVs could lead to higher density development, improved transit use, and more efficient routing. Potential increases in VMT would also need to be mitigated because of related negative environmental impacts. In terms of travel behavior, they could encourage eco-driving and higher vehicle occupancies. In terms of infrastructure, they could reduce congestion and need for capacity projects.

Land Development

The externality associated with land development and associated environmental, economic, and public health effects may be measured by the value of land allocated to automobile infrastructure or by the land that is misused through inefficient development patterns that could otherwise be used for farms, open space, homes, businesses, and other facilities (Delucchi and Murphy 2008). Sprawl is a widely used term in academic and public discourse to describe the development patterns associated with car use (Burchell et al. 2002).

Factors that have influenced land development patterns in the United States can be divided into two categories—market forces and public policy decisions. In terms of market forces, AVs and CVs could increase safety and the convenience of vehicle travel, thereby lowering transportation costs. CVs may increase system efficiency and lower costs. AVs may reduce the non-monetary costs associated with driving. Consumers might travel more miles and take more trips in order to access lower-priced land and rural locations. As another effect, Level 5 AVs could reduce the need for parking adjacent to destinations, which is currently mandated through parking minimums for new development. If this were the case, then parking requirements may be altered or eliminated, and parking in urban areas could be reused for other land uses that more directly benefit society.

Mobility

The limited mobility of older adults, youths under age 16, and individuals with disabilities can be viewed as a negative externality of the existing transportation system, which strongly favors transportation in personal automobiles. AVs represent an opportunity to reduce this negative externality. By leveraging the existing infrastructure that favors motor vehicles, fully AVs (Level 5) may offer significant—potentially transformative—improvements in mobility for aging adults, youths, and individuals with disabilities. This is particularly true for those who live in areas with limited alternative modes. The benefits of less-than-full automation (Level 3 and Level 4) and CVs are unclear and probably much less than Level 5 vehicles because of the demands on the human driver behind the wheel, but this limitation may depend on the specific disability.

Summary of How CVs and AVs Could Lead to Positive Societal Outcomes

Several themes emerge from this review of the effects of AVs and CVs across externalities:

- Safety and vehicle efficiency seem to be important factors that affect multiple externalities. If AV and CV technologies increase motor vehicle safety, these improvements would positively affect crashes, congestion, pollution, and mobility.
- Most of the effects on externalities are correlated; in general, if a technology reduces one negative externality (e.g., traffic crashes), it will also reduce other negative externalities (e.g., congestion and pollution). There are two main exceptions:
    - First, if Level 5 AVs increase driving mobility for individuals who lack it, this would increase congestion, pollution, and so forth. In other words, reducing the negative mobility externality may increase other externalities. However, given that equity is a key transportation goal, it seems likely that society would be willing to accept mobility among this population for the benefits it provides to everyone.
    - Second, if society wishes to reap the benefits of safe Level 5 AVs, many driving jobs will be lost. Policy makers may not be able to or may not wish to internalize this effect. Instead, they may wish to mitigate the effects by retraining professional drivers or developing policies to reduce the supply of professional drivers in step with the growth of AVs.
- There is no evidence that CVs and AVs would work at cross purposes. For example, if an AV technology and a CV technology individually increase vehicle efficiency, having both technologies on the same vehicle will not reduce their positive effects and could even increase it.
- AVs and CVs may sometimes decrease and increase the same negative externalities. For example, CVs and AVs may reduce the costs of travel in general, thereby potentially inducing travel demand. This could add to congestion, pollution, and land-use externalities. However, the technologies may simultaneously enable system efficiency

and decrease crashes that cause significant delay, which would reduce congestion, pollution, and land use. The net effects are uncertain.

Enabling Actions of Consumers and Producers of the Technologies

The research team identified actions that would enable positive societal impacts from CVs and AVs but might not be taken because the societal impacts are external to actors' decision making. Separate analyses were conducted for each externality subsequent to determining how CVs and AVs could affect desirable societal outcomes. These enabling actions are listed in Table 3 for CVs and Table 4 for AVs.

A review across externalities shows common actions in which actors should engage. For CVs, producers need to implement effective safety, mobility, and environment applications (through evaluation and testing), and consumers need use them widely and appropriately. The analysis assumes that V2V safety applications will be implemented through federal mandate, so this implementation is not one of the enabling actions. Such actions will benefit crash, congestion, and pollution externalities. *However, there is little evidence from the literature that CV applications will affect land development, mobility, or economic disruption externalities.*

For AVs, producers need to develop and sell AVs that are safe and efficient. They also need to act upon communications with road operators to ensure that the infrastructure (e.g., lane striping) is in place to support safe and efficient operation or to enable the changes and maintenance necessary to ensure operation. To maximize social welfare, consumers need to purchase safe AVs and use them appropriately but not increase their appetite for travel (more trips, more VMT, and more sprawl) or vehicle size (larger vehicles). Shared AVs (SAVs) in particular could offer many of the benefits of AVs while reducing or at least not increasing travel. If, in addition, vehicles are coordinated with transit to solve last-mile connectivity, they could increase the use of transit.

However, not all enabling actions lead to positive outcomes. Some conflicts exist. First, the adoption of Level 5 AVs may contribute to economic disruption for driving professions. As noted, this may be an effect that public agencies seek to mitigate, though they may not internalize it. Second, the increased mobility for aging adults and individuals with disabilities may increase VMT, leading to more congestion and pollution.

Table 3. Enabling Actions of Producers and Consumers of CV Technologies.

Actions of Producers and Consumers *X Indicates a Reduction of a Negative Externality*	**Externalities**				
	Crashes	**Congestion**	**Land Develop-ment**	**Air and Noise Pollution**	**Mobility**
Producers develop and sell interoperable V2V or V2I mobility applications		X		X	
Producers develop and sell interoperable V2V or V2I environment applications				X	
Consumers purchase vehicles with V2V/V2I capabilities	X	X		X	
Consumers purchase and use aftermarket V2V safety applications	X	X		X	
Consumers are attentive to V2V and V2I safety warnings in vehicles	X	X		X	
Consumers use V2V/V2I mobility applications		X		X	
Consumers are attentive to V2V and V2I mobility messages in vehicles		X		X	
Consumers use V2V/V2I environment applications				X	
Consumers are attentive to V2V and V2I environmental messages in vehicles				X	

Table 4. Enabling Actions of Producers and Consumers of AV Technologies.

Actions of Producers and Consumers ***X indicates a reduction of a negative externality.*** ***X(-) indicates an increase of a negative externality.***	**Externalities**				
	Crashes	**Congestion**	**Land Develop-ment**	**Air and Noise Pollution**	**Mobility**
Producer actions					
Producers develop and sell safe AVs	X	X		X	
Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure safe operations and system efficiency (across different use cases/operating conditions)	X	X		X	
Producers develop and sell connected AVs that harmonize traffic flow		X		X	
Private, shared-vehicle services purchase and operate SAVs		X		X	
Private, shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit		X	X	X	
Developers build fewer parking facilities or build parking facilities that can be adapted to other purposes			X	X	
Producers develop and sell AVs that are lower polluting				X	
Producers develop and sell AVs with eco-driving operating objectives				X	
Producers develop and sell Level 5 AVs that are usable by aging adults and individuals with disabilities		X(-)		X(-)	X
Consumer actions					
Consumers purchase safe AVs	X	X		X	
Consumers follow safe AV maintenance and operating procedures	X	X		X	
Consumers purchase connected AVs that harmonize traffic flow		X		X	
Consumers of AVs minimize VMT growth, though the technology decreases travel cost and enables mobility among some who cannot otherwise drive		X		X	
Consumers of AVs do not drive farther for housing, even though the technology decreases travel cost		X	X	X	
Consumers use SAVs rather than privately owned AVs to minimize VMT growth		X	X	X	
Consumers use Level 5 vehicles to avoid parking in urban centers		X(-)	X	X(-)	
Consumers purchase AVs that are lower polluting				X	
Consumers purchase AVs with eco-driving operating objectives				X	
Aging adults and individuals with disabilities (consumers) purchase Level 5 AVs		X(-)		X(-)	X
Aging adults, youths, and individuals with disabilities (consumers) use Level 5 SAVs		X(-)		X(-)	X

The term AVs in this table refers to Levels 3–5. When a specific level of automation is the subject of the action, it is labeled accordingly (e.g., Level 5).

Impacts on Transportation Agencies

Societal benefits from AV or CV technologies may be maximized through the actions (decisions) of their producers and consumers, as indicated in Tables 3 and 4. However, the impact of these actions on state and local transportation agencies is uncertain. In addition, *it is critical that the policy instruments and planning actions that are determined to be useful in internalizing the externalities of AVs and CVs are mindful of potential impacts to transportation agencies.*

Uncertainty with regard to how and when AV and CV technologies will be deployed leads to more uncertainty about the impact of the externalities associated with these technologies on transportation agencies. Agencies are unsure of what enabling technologies will ultimately prevail, when and to what extent they will penetrate the market, the role of regulation in supporting deployment, the impact on capacity or safety, and the response of consumers to these technologies and applications. Furthermore, the time scale for the development and deployment of these technologies is also unknown. Because estimates for AV availability range from five to 20 years, it is difficult to prepare in the near term for the advent of AV and CV systems. If AV systems, and in particular those that do not rely on infrastructure-based CV technologies, are developed and rapidly adopted, it is unlikely that any of the potential impacts presented in this section can be fully prepared for in the near term.

Due to the uncertainty surrounding AV and CV development and deployment, agency perceptions of their future impacts range from marginal improvements in the comfort and convenience of driving to radical transformations in car ownership and travel patterns with both positive and negative effects (Guerra 2015). Absent further testing and actual deployment of these systems, it is difficult to assess the magnitude of these impacts. However, it is possible to identify potential areas of impact to transportation agencies. AV and CV applications and their associated externalities will likely affect transportation agencies under three different categories of impacts:

- **Institutional:** Institutional impacts are those impacts that affect a transportation agency's focus, areas of authority, and/or organizational structure. This includes how an agency prioritizes its responsibilities and chooses to allocate its funding.
- **Operational:** These are impacts on how an agency actually goes about developing, maintaining, operating, and managing transportation infrastructure and transportation-related services.
- **Funding and financing:** These are impacts on the funding and financing sources available for transportation infrastructure and related services.

Institutional Impacts

State and local transportation agencies plan, design, build, operate, and maintain infrastructure while providing various transportation services. Funding issues in recent years have, in many cases, narrowed that focus to certain critical responsibilities at the expense of others. For many state departments of transportation, activities are currently focused on design, construction, and maintenance. However, the penetration of both AV and CV technologies in the domestic fleet could result in an increased need for operations-related activities, which may in turn require changes in institutional structures (Zmud et al. 2015).

This increased reliance on technology and associated CV applications for transportation systems management and operations poses new challenges for transportation agencies, particularly in the realm of institutional knowledge. Transportation agencies have indicated that their departments generally lack the skills and expertise to manage, operate, and maintain these systems themselves (Zmud et al. 2015). Therefore, transportation agencies are increasingly relying on private-sector actors to varying degrees. The wider deployment of CV systems is likely to further shift responsibility for managing, maintaining, and operating intelligent transportation systems (ITS) to the private sector. If public funding is available for these types of activities, then it is possible that transportation agencies can benefit from the advanced knowledge and skill sets that the private sector brings. However, in the event that funding is not sufficient, it is likely that even more responsibility will devolve to the private sector—in this case financing the desired CV infrastructure.

Operational

AV and CV applications could also impact *how* transportation agencies actually develop, maintain, operate, and manage transportation infrastructure and transportation-related services. In other words, AV and CV applications could impact how an agency goes about conducting its day-to-day business.

For example, one of the most effective methods for keeping AVs within their lane and out of oncoming traffic is rumble strips along the center line and road shoulders. Vehicular accelerometers can easily detect the vibrations from the rumble strips and correct the course of the vehicle when it strays (Vock 2015). In the event that AV applications become more widespread and available, transportation agencies may find that they need to dedicate more resources to incorporating this design element into roadways that do not already feature them. Similarly, AV systems will be capable of detecting and interpreting road signs, a function that may improve vehicle performance and safety in the absence of CV infrastructure that has the capability to communicate aspects of roadway geometry such as curve warnings. However, in order for the signs to be read and interpreted, there is likely to be a required minimal level of visibility. In the near term, states and local agencies may therefore need to expend additional time, effort, and resources in replacing older signs or maintaining existing signage to a minimal visibility standard.

CV applications, in particular, hold significant potential to provide positive externalities to transportation agencies. To the extent that the required supporting technology is deployed and that the necessary data are shared, CV applications will allow for advanced traffic control and monitoring activities by transportation agencies. CV applications will allow for better control of traffic through congested intersections by allowing for priority assignment and queueing control, thereby reducing the human error factor associated with traffic incidents occurring at these locations. Another area of potential improvement is asset awareness. The systems supporting CV infrastructure will allow transportation agencies to remotely monitor the health of their transportation assets such as traffic signals, thus reducing the need to send out maintenance crews in order to check asset health.

AV and CV systems could also negatively or positively affect the value of assets made or held by a transportation agency. Transit agencies are one example of entities that could see significant impacts to their investments and assets, most notably to their vehicle fleets. The growth of transportation network companies (TNCs) that reduce the need to own a personal vehicle coupled with automated vehicle deployment could result in fleets of AVs that serve the same purpose as transit—providing mobility alternatives to personal vehicle ownership. Potential users of these services would benefit from the use of a passenger vehicle without having to own one. Uber, the leading TNC in the United States, has unveiled plans to test AVs in concert with the company's ridesharing services (Harris 2015). In the event that these ventures prove fruitful, it is possible that transit services could see decreases in ridership, creating a negative externality with regard to any assets (in this case, vehicles) that are held in excess of the required demand.

However, it is also possible for transportation agencies to benefit from AV deployment. AV and CV applications could be used within agency fleets for any number of applications. One of the most significant impacts to the use of AV systems by transportation agencies is the use of AV sensing and monitoring equipment for improving safety. The sensors used to detect other vehicles and lane departures in an AV application could be used to alert transit operators of bicycle riders and pedestrians in vehicular blind spots. Reductions in incidents between pedestrians and transit vehicles could be particularly beneficial to transit agencies, primarily because these types of accidents often result in a significantly higher degree of personal injury.

AV and CV applications also have the potential to have a long-term impact on transportation agencies in a negative manner. For example, they may render existing investments in ITS technology by state and local agencies obsolete. The data generated by AVs and gathered through a CV communications network can be used to provide ITS-related services without the need for traditional ITS equipment such as traffic cameras. Agencies that have invested heavily in these traditional ITS strategies may therefore see a loss in that investment as their equipment becomes increasingly obsolete.

Additionally, the impact of AV and CV applications on passenger and commercial VMT will impact the value of investments made (or not made) in capacity expansion. If these applications increase VMT, then agencies that are behind in their capacity investments will find that they now have a more significant capacity deficit to address. This deficit will be exacerbated if AV applications require more headway than what is typically required by a human driver because AVs will then need more roadway space in order to safely operate. Conversely, if AV and CV applications result in a decline in VMT or if these applications require less headway than a human driver does, then agencies that have made recent investments in capacity expansion may find that those investments were unnecessary.

Funding

AV and CV applications have the potential to create potentially significant impacts in terms of funding for transportation agencies. These impacts are driven mostly by factors associated with:

- **Trends in vehicle ownership:** There are already indications that a trend is underway in the reduced reliance on ownership of personal vehicles. As noted previously, the growth of TNCs means that transportation system users are less dependent on owning a personal vehicle and can instead use a ridesharing app or shared vehicle when travel is required. State and local transportation agencies therefore could see reductions in revenues derived from vehicle registrations and vehicle sales tax, to the extent that AV application facilitates the growth of TNCs, promotes the sharing economy, and reduces reliance on ownership of personal vehicles.
- **Trends in vehicular fuel efficiency:** One of the few vehicle manufacturers to offer some form of advanced, semi-autonomous driving mode in their current vehicle line is Tesla, with its autopilot feature (McHugh 2015). Tesla models S and X are able to use this autopilot feature through a software update pushed by the manufacturer. What is noteworthy is that Tesla vehicles are electric, meaning that they do not run on traditional fossil fuels and thus do not generate fuel tax revenues for state and federal transportation agencies. As such, the extent to which the automated fleet of the future is composed of electric vehicles is likely to negatively impact fuel tax revenues generated for use by state and federal transportation agencies to build and maintain the roadways used by such vehicles.
- **Impact of AVs and CVs on VMT:** Additionally, the impact of AV and CV systems on overall VMT will impact fuel tax revenues regardless of fuel type. It is unknown at this time whether AV and CV systems will reduce or increase VMT, but the direction of the impact will have a corresponding impact on revenues derived from usage-based taxing mechanisms such as fuel taxes.
- **Impact of AVs and CVs on transit ridership:** The deployment of AV technologies by TNCs could create negative externalities with regard to investments in transit vehicles by transit agencies. Furthermore, if new services reduce transit ridership, they will also reduce revenues from transit fares and the allocations of federal funds, which are based on ridership estimates.
- **Impact of AV and CV on moving violations:** AV and CV applications are anticipated to increase safety by reducing the incidence of driver error. Therefore, they can also be expected to reduce the incidence of driver behavior that constitutes a moving violation that results in the issuance of a ticket. Thus, AV and CV applications could negatively impact local agencies that derive significant amounts of revenue from these types of traffic violations.

Table 5 summarizes potential impacts on transportation agencies. While presented independently, all three of these families of impacts are related. Funding and financing impacts may shift how a transportation agency prioritizes its activities at the *institutional* level, which in turn impacts how assets are deployed and managed at the *operational* level.

Table 5. Impacts on Transportation Agencies.

Potential AV/CV Outcome	Transportation Agency Impacts
Institutional impacts	
AV and CV systems could reduce crashes and increase overall safety	Increase focus on non-safety goals, such as maintenance and preservation, systems management and operations, and data management
Commercial and transit AV fleets could reduce reliance on professional drivers, which increases safety by reducing vehicle incidents	
AV and CV systems could raise road users' expectations for ITS-related services for which transportation agencies lack institutional expertise	Increase reliance on contracting, new relationships with the private sector
AV and CV systems could require physical infrastructure assets, data management, and ITS services for which agencies lack funding	Increase reliance on private-sector investment models
AVs could require changes in basic road design and geometry in the long run to accommodate safe and efficient operations	Change roadway construction practices
AV and CV systems could increase reliance on data-intensive services and applications	Increase responsibility for data integrity, security, privacy, and analytics
AV and CV could provide added value to existing operations and maintenance, particularly safety benefits in transit operations	Change maintenance/operations practices
CV applications could provide asset health information	Improve operational awareness
Operational impacts	
Technology assets could become obsolete with rapidly changing technology	Outdate ITS investments
SAVs could increase average vehicle occupancy and usage, improving system management and reducing congestion without the need for traditional ITS	
Various communications technologies used in CV and AV applications could provide ITS-type traveler information to drivers within the vehicle itself	
AVs or SAVs could reduce demand for transit and other non-passenger vehicle modes, including traditional paratransit	Reduce emphasis and stimulate loss of value in transit investments
SAVs or usage of Level 5 AVs could reduce need for urban parking	Reduced emphasis and stimulate loss of value in parking investments
AV systems could increase need for visible lane striping, more visible signs, and removal of roadway obstructions	Increase maintenance requirements
Commercial AV fleets could increase volumes (by lowering shipping costs), thereby increasing wear and tear on the system	
AV systems could increase the development of low-density suburban development by lowering the cost of commuting, thereby increasing the infrastructure network to be maintained	

Table 5. Impacts on Transportation Agencies (Continued).

Potential AV/CV Outcome	Transportation Agency Impacts
CV systems could facilitate the more efficient movement of vehicles through congested intersections	Mitigate capacity issues associated with recurring and non-recurring congestion
AV and CV systems could provide enhanced transportation system asset awareness by transportation agencies	
AV and CV systems could allow transportation agencies to better use existing capacity through various ITS management and operations practices	
CV systems could provide travelers with dynamic, real-time information on construction projects that impact mobility	
AV and CV systems could provide drivers with information on impending bad weather and weather-related road conditions	
AV systems could lower the cost of driving, thus increasing VMT	Exacerbate capacity deficit
AV applications could require additional headway relative to human drivers, thus reducing available capacity	
Funding impacts	
AV and CV applications could increase passenger and commercial VMT, increasing the costs associated with maintaining and operating roadways	Exacerbate funding issues
AV and CV systems could increase need for visible lane striping, more visible signs, removal of roadway obstructions, physical infrastructure to support CV applications, and detailed infrastructure-related data to support CV applications	
SAVs could reduce the amount of revenue derived from vehicle registration fees	Reduce vehicle registration, sales tax, or licensing revenue
SAVs could bring about a decline in vehicle ownership and then a decline in vehicle production (and associated decline in vehicle sales)	
SAVs could result in fewer professional drivers and traditional taxi services, thus bringing about a decline in revenues from sources such as commercial driver licenses and taxi medallions	
AVs could be deployed with electric-motor-based technologies	Reduce fuel tax revenue
AV and CV systems could increase VMT and include technology for usage-based revenue measurement	Increase revenue from mileage-based usage
AV and CV systems could reduce driver error	Reduce revenues from moving violations
AVs or SAVs could reduce mass transit utilization	Reduce transit fares and federal funding associated with ridership levels

3. Role of AVs and CVs on Specific Externalities

This chapter reviews literature pertaining to the role of AVs and CVs in mitigating or exacerbating externalities (e.g., traffic crashes, congestion, pollution, land development, mobility, and economic disruption to the driving profession) through examination of five questions:

- What is the externality?
- How significant is it?
- What factors contribute to the externality?
- How could CVs and AVs lead to desirable outcomes?
- What actions of producers and consumers would enable these outcomes but might not be taken because the societal impacts are external to their decision making?

This chapter contains summaries of the detailed briefing papers that are provided as appendices. The answers to these questions lead directly to the identification of policy instruments and planning actions to influence the actions of producers and consumers that are beneficial for society but might be external to their decision making.

Traffic Crashes

What Is the Externality?

Traffic crash externalities occur because when individuals drive a vehicle, they not only increase their own risk of a crash but also increase crash risks for other motorists as well as pedestrians and bicyclists. Individuals can internalize traffic crash costs by refraining from driving, exercising greater care while driving, or insuring themselves (and vehicles) against possible damages that occur as a consequence of driving (Jansson 1994). Sometimes the total costs of a crash are not borne by the individual (Edlin and Karaca-Mandic 2006, Parry et al. 2007, Anderson et al 2014). Social costs or externalities are the costs inflicted on fellow road users and the spillover effects on the rest of society. For example, the cost of medical care after a crash is certainly borne by the individual in the form of payments for insurance, deductibles, or uncovered costs and uninsured expenses. It is also borne by society through higher insurance premiums and the diversion of medical resources from other needs such as medical research or basic medical health (NHTSA 2015a).

How Significant Is It?

NHTSA estimated the total economic cost of motor vehicle crashes in the United States in 2010 as $242 billion (NHTSA 2015a). The cost components included productivity losses, property damage, medical costs, rehabilitation costs, congestion costs (including travel delay, excess fuel consumption, and increased environmental impacts), legal and court costs, emergency services (such as medical, police, or fire services), insurance administration costs, and costs to employers. Such costs for 2010 were equivalent to $784 for every U.S. resident and 1.6 percent of the U.S. gross domestic product. When intangibles are factored in (e.g., pain and reduced quality of life), the total societal harm from motor vehicle crashes in 2010 was $836 billion.

What Factors Contribute to It?

NHTSA analysis has identified three categories of factors that cause crashes (about 2 percent of the immediate reasons for a pre-crash event as collected in NHTSA's National Motor Vehicle Crash Causation Survey were "unknown") (NHTSA 2015b):

1. **Driver related:** Human error accounted for 94 percent of all crashes at the national level in the NHTSA analysis of data from 2005 to 2007. Driver-related causes of crashes are broadly classified into the follow types of errors:
    - **Recognition (41 percent):** Recognition errors include those related to a driver's inattention, internal and external distractions, and inadequate surveillance.
    - **Decision (33 percent):** Decision errors include driving too fast for conditions or too fast for curves and making false assumptions of others' actions or illegal maneuvers. Alcohol-involved crashes involve both perception problems (recognition errors) and impaired judgment (decision errors).
    - **Performance (11 percent):** Performance errors pertain to executing an improper motor response, such as panicking, overcorrecting, or having poor directional control.
    - **Non-performance (7 percent):** Sleep was the most common reason among non-performance errors.
2. **Vehicle related:** Mechanical issues with vehicles accounted for 2 percent of all crashes. These were identified primarily as problems with tires, brakes, steering column, and so forth.
3. **Environment related:** Roadway or weather conditions accounted for 2 percent of all crashes. Nearly half of the crashes in this category were attributed to slick roads (e.g., ice and loose debris).

Both CV and AV technologies have the opportunity for creating desirable outcomes in relation to the traffic crashes externality.

Safety is the primary benefit of V2I and V2V applications. Safety warnings enable drivers to take actions that could reduce the severity of collisions or avoid them. Warning systems simply warn the driver when a collision is likely but do not automatically apply the brakes. Even so, research has indicated that V2V safety applications address nearly 80 percent of all-vehicle target crashes, and V2I safety application areas would prevent nearly 60 percent of single-vehicle crashes and nearly 30 percent of multi-vehicle crashes (Najm 2010, Eccles 2012). These outcomes depend on the extent of V2I deployment, market penetration of vehicles with V2V communication capability, the effectiveness of specific applications, the impact of spectrum sharing and V2V communication congestion, the precision of the V2V positioning, and the driver-vehicle interface performance.

While safety is also a primary motivation for AV development, other motivations expressed by producers include mobility, environment, convenience, and multi-tasking benefits. AVs represent a switch in responsibility for the driving task from human to machine. As more of the driving task is switched to the automated driving system as with Levels 3–5, these vehicles may lead to more desirable outcomes.

How Could CVs and AVs Lead to Desirable Outcomes?

AVs should be able to mitigate a large portion of accident risk stemming from human error, which accounts for 94 percent of motor vehicle crashes. That said, research has identified three categories of challenges in terms of fulfilling the societal safety benefits of AVs, at least in the near term:

- **Driver performance gaps**: Level 3 AVs represent a balancing act that attempts to provide drivers with the benefits of autonomy—such as not having to pay attention—while ensuring they are ready to take over the wheel when needed. There are situations in which safety may not be enhanced, such as if a driver were texting, reading, or sleeping at the time of the request to intervene (Trimble 2014). For this reason, some producers (e.g., Google) are targeting automation levels above three because it presents a challenge in how to safely transfer control.
- **Potential new types of vehicle errors**: As the driving task is switched from humans to machines, many technologies (e.g., sensors, motion control, trajectory planning, driving strategy, and situational awareness) need to operate effectively so that the vehicle performs at least as well as a human driver (Trimble 2014). AV technology represents complex machines that need to be adequately tested prior to market introduction and, after introduction, adequately maintained and updated by owners. Tesla's early release of its autopilot software update is an example; for some drivers with hands off the wheel, the vehicle sometimes veered out of its lane. Cybersecurity risks also pose a new type of vehicle error. Cybersecurity—in the context of vehicle systems—refers to security protections for systems in the vehicle that actively communicate with other systems or other vehicles (Garcia et al. 2015). While cybersecurity issues are a challenge for CVs, security becomes a bigger concern with Level 4 and Level 5 vehicles, in which software and connectivity play a much bigger and more critical role for the safe driving of vehicles. In case of cyberattack, the safety of passengers in an AV and other road users could be at risk. In case of hacking and stopping a fleet of AVs, the transportation system could be halted with potential safety reduction (even though no real case of malicious car hacking has been reported yet).
- **Operating conditions constraints**: Another limiting factor was noted by Smith et al. (2015) in developing an AV benefit estimation framework for USDOT. The analysis suggested that AVs may only operate under specific conditions, and these conditions can be constrained by vehicle location, speed, and/or dynamics. For example, it is much

less demanding for an AV to stay centered in a lane on a highway than on a road in a crowded city where lane markings can be less visible and bicyclists and pedestrians travel alongside cars and trucks. Safety benefits are enhanced through widespread use of AVs and concomitant reduction of human errors.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External to Their Decision Making?

For CVs and AVs to have the desired outcomes of reduced traffic crashes, it is important that CV applications enable drivers to operate a vehicle more safely than they would otherwise and that AVs are at least as safe as a human driver. Researchers identified seven distinct actions that producers and potential consumers of vehicles equipped with AV and CV technologies can take to realize these beneficial outcomes:

1. Producers develop and sell safe AVs. (This action encompasses Levels 3–5, so it would pertain to such specifics as producers developing and selling Level 3 AVs with the proper human-machine interface, thus reducing driver performance gaps.)
2. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure safe operations (across different use cases/operating conditions).
3. Consumers purchase vehicles with V2V/V2I capabilities.
4. Consumers purchase and use aftermarket V2V safety applications.
5. Consumers are attentive to V2V and V2I safety warnings in vehicles.
6. Consumers purchase safe AVs.
7. Consumers follow safe AV maintenance and operating procedures.

Congestion

What Is the Externality?

As the number of vehicles on a road increases past a certain density, vehicle speed and throughput decrease, causing congestion. When a driver uses a busy road, he or she adds to, but does not pay for, the congestion that other drivers experience. As congestion worsens and traffic moves less efficiently than it would otherwise, people lose time, waste fuel, and worsen pollution. These effects are external economic and public health costs imposed on society.

How Significant Is It?

Travel delays due to traffic congestion caused drivers to waste more than 3 billion gallons of fuel and kept travelers stuck in their cars for nearly 7 billion extra hours—42 hours per rush-hour commuter (Schrank et al. 2015). The total cost to the United States was $960 per commuter, or $160 billion for the nation as a whole.

What Factors Contribute to It?

Congestion can be recurring and non-recurring. Recurring congestion is caused by shortages of road supply and excesses of driving demand, and by inefficiencies in operating or managing the transportation system. Non-recurring factors include incidents such as motor vehicle crashes, construction, weather, and other temporary disturbances (Paniati 2003).

How Could CVs and AVs Lead to Desirable Outcomes?

CVs and AVs are likely to affect both recurring and non-recurring factors that contribute to congestion.

CV safety applications could mitigate non-recurring congestion by reducing delays caused by safety incidents overall or in specialized contexts such as work zones and harsh atmospheric conditions. CV mobility applications could positively impact recurring congestion through increasing system efficiency by enabling vehicles to coordinate their actions through a traffic management center, thereby proactively predicting queues and congestion and optimizing traffic flow. These benefits would be maximized if there were widespread adoption of vehicles with V2V capabilities, widespread V2I infrastructure, and interoperability among mobility applications.

AVs could potentially drive with greater precision and control than humans (Smith 2012). This capability would enable a reduction in crash-related delays. In addition, this capability could plausibly enable infrastructure operators to redesign aspects of their facilities to accommodate more traffic and have a positive impact on recurring congestion. For example, by reducing lane size and shoulder width, an agency could restripe a road and add a lane. If this were to occur, it would require all (or nearly all) vehicles to be capable of driving with a high level of control. Additionally, new lanes may be possible only in areas with sufficient spacing. Finally, SAVs may offer benefits for congestion as well. Provision of SAVs could reduce the VMT of users and lead to higher density development, potentially resulting in further lower per-trip VMT. SAVs could be used to provide first-mile/last-mile linkages to mass transit systems or to facilitate ridesharing by pooling occupants, thus reducing congestion.

AVs and CVs could affect congestion in potentially negative ways as well. AV and CV mobility applications could decrease the actual and perceived costs of driving, such as the opportunity cost of a motorist's time, fuel costs, parking costs, and reduced costs associated with fewer crashes. Under fully AVs, the opportunity costs of motorists' time could be completely removed through the motorists not even being present in the vehicle, which could enable many different services and opportunities. When the cost for an activity decreases, typically demand for that activity will increase. In this case, AVs and CVs could induce additional travel demand.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External to Their Decision Making?

Because AVs and CVs are likely to affect congestion in both positive and negative ways, it is important to identify actions that might enable the beneficial outcomes for society. Researchers identified 16 actions that producers, providers, and potential consumers can take to realize these beneficial outcomes. Several of these derive directly from the actions that producers and consumers can take to improve safety and reduce crashes, which are a major source of delay.

1. Producers develop and sell interoperable V2V or V2I mobility applications.
2. Producers develop and sell safe AVs.
3. Producers develop and sell connected AVs that harmonize traffic flow.
4. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency *and* safe operations (across different use cases/operating conditions).
5. Private shared-vehicle services operate SAVs.
6. Private shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit.
7. Consumers purchase vehicles with V2V /V2I capabilities.
8. Consumers purchase and use aftermarket V2V safety applications.
9. Consumers use V2V/V2I mobility applications.
10. Consumers are attentive to V2V and V2I safety and mobility messages in vehicles.
11. Consumers purchase safe AVs.
12. Consumers follow safe AV maintenance and operating procedures.
13. Consumers purchase connected AVs that harmonize traffic flow.
14. Consumers of AVs do not significantly increase overall travel demand, though technology reduces the non-monetary costs of driving.
15. Consumers of AVs do not drive farther for housing, even though the technology decreases travel cost.
16. Consumers use SAVs rather than privately owned AVs, which reduces their travel demand or trip generation.

Pollution Externality

What Is the Externality?

Automobiles emit local air pollutants (e.g., particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide) and global air pollutants (greenhouse gases) when they combust fuels, primarily fossil fuels. Thus, when someone drives a vehicle, he or she reduces the air quality of those in the surrounding area and imposes the costs of climate change—a global effect—on everyone. These effects impose public health, environment, and economic costs on society, both locally and globally (Colvile et al. 2001, Krzyżanowski et al. 2005)

Vehicles are also loud. There is noise from engines, the contact between wheels and the road, braking, and honking. When someone drives, he or she adds to the noise pollution of those who live and work in the area. Noise pollution has impacts on public health and on economic development (Delucchi and Hsu 1998).

Greenhouse Gas Emissions and Climate Change

In 2013, transportation sources accounted for about 27 percent of total U.S. greenhouse gas (GHG) emissions, making it the second largest contributor of U.S. GHG emissions after the electricity sector. GHGs affect the amount of heat retained by the Earth's atmosphere, and the resulting climate change impacts nearly every facet of human and natural life. It has resulted in increases to global surface temperature by approximately 0.8°C over the past century (NAP 2010) and is projected to increase temperatures still further. The World Bank estimates that the costs of adapting to a potential 2°C warmer world between 2010 and 2050 could range from $70 to 100 billion per year. GHG emissions are estimated at 1.7¢ per mile for an average car and 2.4¢ per mile for light trucks (World Bank 2010).

Local Air Pollution

Gasoline-powered vehicles emit carbon monoxide, nitrogen oxide, and hydrocarbons, otherwise referred to as volatile organic compounds. Unlike global air pollution, which affects nearly everyone across the planet (though to varying degrees), local air pollution effects are felt primarily by those closest to the source, with externality costs varying by *who* is exposed to the air pollution (some persons are more vulnerable to potentially harmful air quality effects) and the *amount* of air pollution inhaled by an individual, also known as exposure.

Noise

Traffic noise is considered one of the important sources of noise pollution (Martin et al. 2006). Evidence indicates that noise pollution may have an adverse impact on human health (Georgiadou et al. 2004) and has been stated as a serious health hazard.

How Significant Is It?

Litman and Doherty (2015) estimated urban peak local air pollution costs at approximately 5¢ per average automobile mile. Urban off-peak costs are estimated at a slightly lower 4¢ per VMT to account for smoother road conditions and less stop-and-go traffic. Rural driving air pollution costs are estimated to be an order of magnitude lower, at 0.4¢ per VMT (largely due to fewer exposed people).

Noise-related health hazards cause damage to humans ranging from annoyance to mental illness and even death (Mato and Mufuruki 1999, Nelson 1987, Morrell et al. 1997). Permanent hearing loss by long-term exposure to noise has been reported by Nelson. Noise effects may include annoyance, deterioration of sleep quality, and stress-related ischemic heart disease. Most studies place average automobile noise costs at 0.1¢ to 2¢ per vehicle mile (VTPI 2015).

What Factors Contribute to It?

One can attribute the total emissions in the road transportation segment across four primary categories, as noted by the Transportation Research Board (Cohen 1995), including:

1. Vehicle factors, such as vehicle ownership patterns, the quantity of vehicles produced, the type of vehicles produced, and vehicle fuel source, which all influence environmental outcomes.
2. Travel factors, such as trip generation, trip distribution, mode split, and traffic assignment (or route choice, at the individual vehicle level).
3. Driver behavior factors, including acceleration, braking and speed selection patterns that would be influenced by automated driving, participation in cooperative adaptive cruise control platoons, and whether or not drivers use eco-driving techniques.
4. Infrastructure factors, consisting of the provision and operation of the transportation system, including the role of V2I implementations and overall system efficiency.

How Could CVs and AVs Lead to Desirable Outcomes?

AVs and CVs can affect nearly all of the factors that contribute to emissions. Researchers grouped these desirable outcomes by these four factor categories:

- Vehicle related:
  - Safer AVs and CVs mean fewer crashes and lower replacement rates, which would reduce emissions from vehicle production.
  - Level 5 vehicles, particularly shared-use ones (SAVs), should lead to lower vehicle ownership, fewer parking needs, and fewer associated environmental costs for parking provision.
  - Fewer numbers of SAVs and personally owned Level 5 vehicles may be needed than current conventional vehicles. This decrease may lead to lesser production quantities and lower resulting manufacturing-related emissions. Greater AV utilization (less time between sequential trips) could reduce cold-starting emissions.
  - Provision of right-sized SAVs (vehicle occupancy matched to travel party size) may result in lower operating and manufacturing emissions.
  - AVs do not become larger on average than the current fleet, which would otherwise result in greater operating and manufacturing emissions and more noise.
  - CV information may be used to identify available electric vehicle (EV) charging stations, which encourages adoption of EVs and leads to lower emissions in certain states, depending on the energy grid, and lower noise impacts.
- Travel related:
  - Provision of SAVs could lead to higher density development, potentially resulting in lower per-trip VMT.

    - SAVs could be used to provide first-mile/last-mile linkages to mass transit systems or to facilitate ridesharing by pooling occupants, thus reducing operating emissions.
    - More efficient routing may be used to avoid congestion and incidents, and users may use CV information to identify and choose the most fuel-efficient routes.
    - Overall travel and VMT do not increase, which would cause more operating emissions and noise impacts.
- Driver behavior related:
    - Customized real-time CV information may be used to encourage eco-driving behavior, thus leading to reduced operating emissions.
    - AVs may choose vehicle speed, acceleration, and braking control more effectively, resulting in more efficient operation and lower operating emissions.
    - Connected AV platoons using cooperative, adaptive cruise control should see reduced wind resistance, higher fuel efficiency, and lower operating emissions.
- Infrastructure related:
    - V2I applications focused on enhancing system efficiency could smooth traffic and ease congestion, resulting in lower per-mile operating emissions.
    - Increased capacity realized through enhanced system efficiency gains could mean fewer road capacity addition projects and resulting construction emissions.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External to Their Decision Making?

There are many ways in which producers and consumers could enable these desirable environmental outcomes. Several of these derive directly from the actions that producers and consumers can take to improve safety and reduce congestion, along with associated pollution.

1. Producers develop and sell interoperable V2V or V2I environmental and mobility applications.
2. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency *and* safe operations (across different use cases/operating conditions).
3. Producers develop and sell AVs that are lower polluting.
4. Producers develop and sell AVs with eco-driving operating objectives.
5. Consumers purchase vehicles with V2V/V2I capabilities.
6. Consumers purchase aftermarket V2V safety applications.
7. Consumers use V2V/V2I environmental, mobility, and safety applications.
8. Consumers are attentive to in-vehicle V2V and V2I environmental, mobility, and safety messages.

9. Private shared-vehicle services operate SAVs.
10. SAV operators prioritize ridesharing and linkages with line-haul mass transit.
11. Developers build fewer parking facilities or build parking facilities that can be adapted to other purposes.
12. Consumers purchase AVs that are lower polluting.
13. Consumers purchase AVs with eco-driving operating objectives.
14. Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth.
15. Consumers of AVs do not significantly increase overall travel demand though the technology decreases travel cost and enables mobility among some who cannot otherwise drive.
16. Consumers of AVs do not drive farther for housing even though the technology decreases travel cost.

Land Development

What Is the Externality?

Automobile use has influenced the form and extent of land development in the United States. As cities expanded to provide housing for a growing population in the 20th century, the introduction and proliferation of the personal automobile reduced transportation costs, enabled decentralization of both residences and jobs, and resulted in a large portion of land being allocated for highways, streets, and parking. The externality associated with land development may be measured by the value of land allocated to automobile infrastructure that could otherwise be used for farms, open space, homes, businesses, and other facilities, with associated environmental, economic, and public health effects (Delucchi and Murphy 2008).

The concept of sprawl is also associated with this externality. Sprawl is a widely used term to describe the low-density, inefficient land-use patterns associated with automobile use (Burchell et al. 2002). While there is no consensus on whether sprawling development is inherently negative or that automobile use is its cause, CV and AV technologies have the potential to influence the land-use patterns that contribute to the externalities of development.

How Significant Is It?

The externality is potentially quite significant. The market value of land for public roads and right-of-way was estimated at $384 billion in 1991. The price per acre ranges from $60,000 for freeways and $105,000 for local roads in urban areas to $840 for freeways and $6720 for local roads in rural areas (Delucchi and Hsu 1998). State departments of transportation spent $15 billion on new construction and added-capacity reconstruction on interstates and arterials. Compact development could reduce sprawl-related road infrastructure costs by about 25 percent (Burchell et al. 2002).

What Factors Contribute to It?

Factors that have influenced land development patterns in the United States can be divided into two categories—market forces and public policy decisions. Land development is driven by the demand in the market for housing and employment activities. The price of a plot of land reflects the potential development value of that land; centrally located land tends to be assigned more worth than remote, undeveloped land. Households, businesses, and developers make decisions about land, housing, and office space based on the costs and trade-offs presented in the market. However, land markets are not perfect markets—pricing is subject to speculation, all costs are not fully internalized, and government policies alter the market (Ewing 2008).

In addition, federal and local government policies related to land use, zoning, transportation, and homeownership have created market distortions that impact land development and, in some cases, contribute to sprawl. Suburban homeownership has been implicitly subsidized by tax policies, including property tax and mortgage interest deductions and federally insured loans (Ewing and Hamidi 2015). Private vehicle use is also implicitly subsidized by free parking around developments. These policies increase the amount of housing that people are willing to consume and favor single-family home development outside of urban areas.

How Could CVs and AVs Lead to Desirable Outcomes?

The following are some of the potential links between AVs and CVs and the market and policy factors that influence land development patterns:

- Transportation costs, both monetary and non-monetary, currently moderate the distance one is willing to travel to access lower-priced land for development. Automobile availability greatly increased mobility and improved accessibility outside of the central city core (Glaeser and Kahn 2003). As with the introduction of the automobile, AVs and CVs have the potential to decrease the non-monetary costs of driving. CVs are primarily designed to provide safety benefits but may also reduce congestion, increase mobility, and improve the driving experience. AVs may also contribute to increased efficiency of the vehicle and greatly reduce the burden of driving, especially as the driver is progressively able to disengage from the driving task with higher levels of automation. If fully automated Level 5 AVs were allowed to drive with no human driver present in the vehicle, time and other non-monetary costs of vehicle travel would be further diminished. Lower transportation costs provided by CVs and AVs and a continued demand for lower-density housing may encourage development on rural, lower-cost land.
- Automobile travel is already the selected mode choice for most travelers in the United States. CVs and AVs offer potential safety and convenience benefits that could further drive preferences for automobile travel. The higher safety, lower congestion, and improved driving experience offered by CVs could similarly continue or increase the current market demand for automobile travel. On the other hand, SAVs could contribute to a shift away from personal vehicle ownership to shared fleets. If advanced vehicles are introduced through shared fleets, then car-ownership levels may decline. It is

unclear how this would impact driving. Automated shared fleets could decrease the number of trips made by vehicles as well as dampen VMT growth, because travelers pay based on the marginal cost of each additional mile traveled, or increase vehicle travel due to the same benefits attributed to personal AVs.

- Parking effects will be experienced differently in urban and rural areas. In urban areas, AVs may reduce the need for parking adjacent to destinations. AVs and CVs may be able to park in smaller spaces with more precision than human drivers, and higher-level AVs are expected to have the ability to drive and park at home or in remote parking areas. This would allow for more cars to fit in less space and in non-adjacent locations to free up centrally located land for other uses. In a shared-vehicle scenario, a vehicle could attend to other trips after dropping off a passenger—reducing the need for parking at each destination. Changes to parking needs will only occur with high levels of AV/CV adoption and would require changes to the parking requirements, which currently mandate parking minimums for new development. In the long term, this may stimulate infill development as existing parking infrastructure in high-rent areas is no longer needed. In contrast, in rural areas, the unbundling of parking adjacent to activity centers could lead to the construction of parking on cheaper, undeveloped land—following the same patterns seen with previous sprawl development.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External to Their Decision Making?

There are several ways in which producers and consumers could enable positive outcomes and mitigate negative ones:

1. Consumers use SAVs rather than privately owned AVs, which reduces their travel demand or trip generation.
2. SAV operators prioritize ridesharing and linkages with line-haul mass transit.
3. Consumers use Level 5 vehicles to avoid parking in urban centers.
4. Developers build fewer parking facilities, or build parking facilities that can be adapted to other purposes.

Mobility

What Is the Externality?

Access to transportation is essential for a high quality of life for nearly all Americans yet is often a significant challenge for aging adults, youth under age 16, and individuals with communicative, mental, or physical disabilities. Many live in car-dependent areas but do not drive, and transit alternatives may be geographically inconvenient or inaccessible. The Americans with Disabilities Act (ADA) mandates that transit authorities operating a fixed-route system provide paratransit or a comparable service to individuals with a disability (U.S. Department of Justice 2016). ADA paratransit is a high-demand alternative, but the average cost of a trip for passengers is almost twice as expensive as the same fixed-route transit trip (Government Accountability Office 2012).

The lack of mobility has serious consequences. These individuals face the risk of social isolation, and the resulting lower quality of life is well documented and can result in diminished support networks, loneliness and depression, and decline in health (Drainoni et al. 2006, Frye 2013, Marottoli et al. 1997, Metz 2000, Reichard et al. 2011).

The limited mobility of aging adults, youth under age 16, and individuals with disabilities can reasonably be viewed as a negative externality of the existing transportation system, which strongly favors transportation in personal automobiles. Consumers who own and operate a vehicle do not pay the full cost of their cars due to a variety of explicit and implicit driving subsidies (Crouse 2000, Delucchi and Murphy 2008, Litman 1997). The artificially low cost of driving reinforces the preeminence of private vehicle ownership and use when public and private transportation resources are prioritized. This amplifies the mobility challenges of non-drivers and decreases the resources available to fund alternatives that would address their needs (Crouse 2000, Glaeser and Kahn 2003, Williams 2010).

How Significant Is It?

The literature does not offer estimates of the cost of this externality. However, the number of individuals affected and the expenditures on paratransit suggest that it is significant: it affects tens of millions of people and costs many billions of public dollars annually.

The population of Americans over the age of 65 was 43.1 million in 2012 and is projected to increase to 83.7 million in 2050 (Ortman et al. 2014). Approximately 80 percent of the 45 million Americans over the age of 65 live in car-dependent locations, and nearly 90 percent wish to age in place (Dudley 2015). However, only about 83 percent of adults 70–79 years old and about 62 percent of adults over 80 years old drive, compared to 94 percent of adults 50–59 years old (Santos et al. 2009). In addition, disparities in available transportation alternatives exist between urban and rural environments (Burkhardt et al. 2002, Jones et al. 2007).

In the 2010 Census, 56.7 million individuals identified as having either a communicative, mental, or physical disability (18.7 percent of the total population). Out of this group, 38.3 million (12.6 percent) reported a severe disability, such as being unable to perform activities of daily living without assistance (e.g., going outside the home, dressing, and eating), being deaf, and being blind, among others (Brault 2012). Approximately 35 percent of individuals with disabilities do not drive, compared to 12 percent of the non-disabled population (U.S. Department of Transportation 2003).

Americans with disabilities significantly depend upon public transit. However, they expressed having a harder time than their peers without disabilities in obtaining the transportation they require to be independent (12 percent versus 3 percent), and the top two reasons given for this were no or limited public transportation (33 percent) and not having a car (26 percent) (U.S. Department of Transportation 2003).

The cost of providing paratransit services in the United States is many billions of dollars. The five transportation agencies with the highest ADA expenses alone spend $1 billion annually on these services (Government Accountability Office 2012). These costs give a sense of the scale of the challenge of providing transportation to aging individuals and individuals with disabilities and the importance to American society of doing so.

What Factors Contribute to It?

Researchers identified three important factors that contribute to the limited mobility of aging adults and individuals with disabilities:

- **Limited availability of alternative transportation modes:** As noted, approximately 80 percent of retirement-age adults live in car-dependent communities. In isolated urban and rural environments, driving a car where public transportation alternatives or pedestrian access is unavailable may be the only option for transportation for the elderly and disabled (Frye 2013). The top reason given by individuals with disabilities who reported having difficulty obtaining transportation was no or limited public transportation (U.S. Department of Transportation 2003).
- **Difficulty using alternative modes:** Research shows that individuals with disabilities are significantly more likely to experience difficulties using transit than those who do not—32 percent versus 23 percent on buses, for example (Thatcher et al. 2013). While paratransit may provide an alternative, this may not be available to everyone. For instance, aging adults with frailty or chronic conditions may not be able to use transit but may also not be eligible for ADA-related paratransit (Bailey 2004).
- **Cost of driving and other transportation modes:** Income is a determinant of mobility because it affects the ability to purchase a new vehicle, maintain it, or live in a neighborhood connected to different modes of transportation (Burkhardt et al. 2002). As noted, paratransit can cost, on average, up to twice as much as fixed-route services. These costs can be prohibitive for aging adults and individuals with disabilities. In 2014, 28.5 percent of individuals with a disability and 10 percent of aging adults had a yearly income that was below the poverty line (DeNavas-Walt and Proctor 2015).

These are not *all* the factors that contribute to the mobility challenges. There may be social, economic, and other reasons. However, these are the factors researchers have concluded to be most relevant for a discussion of the externalities of AVs and CVs.

How Could CVs and AVs Lead to Desirable Outcomes?

AVs represent an opportunity to reduce this mobility externality (Bradshaw-Martin and Easton 2014). By leveraging the existing infrastructure that favors motor vehicles, fully AVs (Level 5) may offer significant—potentially transformative—improvements in mobility for aging adults and individuals with disabilities, particularly those who live in areas with limited alternative modes.

The extent of this benefit depends on two key factors: usability and cost. First, individuals must be able to use Level 5 AVs. Individuals who are otherwise independent, such as aging adults who have voluntarily stopped driving and individuals with certain disabilities, are likely to experience the fewest barriers to use and greatest gains. For many, AVs will need to be modified for better accessibility. Second, AVs may be expensive, at least at first. For many aging adults, youths, and individuals with disabilities, the costs of a personally owned vehicle are prohibitive; the costs of an AV are even more so. Shared models of use—through either private shared mobility providers or transit—may offer affordable ways of increasing mobility at an affordable cost.

The benefits of less-than-full automation (Level 3 and Level 4) and connectivity are unclear and probably much less than that of Level 5 vehicles because of the expectation of a human driver behind the wheel.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External to Their Decision Making?

Researchers identified five distinct actions that producers, providers, and potential consumers of L5 vehicles can take to realize these beneficial outcomes:

1. Producers develop and sell Level 5 vehicles that are usable by aging adults, youths, and individuals with disabilities.
2. Private shared-vehicle services purchase and operate SAVs.
3. Aging adults and individuals with disabilities (consumers) purchase Level 5 AVs.
4. Aging adults, youths, and individuals with disabilities (consumers) use Level 5 SAVs.

4. Policy Instruments and Planning Activities

The research team undertook a review of the literature with the intent of uncovering academic publications, governmental reports, and other resources detailing the policy instruments governments could use to internalize externalities in road transport. The literature revealed a variety of different potential strategies to internalize externalities. To help organize, analyze, and apply the research, the team sorted policy instruments (those that specifically internalize externalities) into two main categories seen in the literature: economic instruments and non-economic instruments (Hepburn 2006). Policy instruments from both categories can internalize externalities; however, the main distinction lies in how these tools accomplish their goal. In addition to policy instruments, researchers also identified transportation planning activities that might be used to internalize externalities.

This chapter describes the types of possible policy instruments, the circumstances under which the policy instruments are best suited, and the process of aligning policy instruments and planning activities to actions of producers and consumers of AVs and CVs that would lead to desirable societal outcomes.

Economic Instruments

Economic instruments are tools that "provide an explicit price signal to regulated firms and individuals" (Hepburn 2006). With these tools, governing bodies are able to affect an externality in two ways:

- Directly, by changing the price by imposing a tax or providing a subsidy.
- Indirectly, by imposing controls on the quantity of a good that is produced or sold—most often through a cap-and-trade-style system.

Either of these economic instrument types provides an incentive to market participants to, ideally, change their behaviors that negatively affect society (Van Essen et al. 2008).

The literature identifies two circumstances where economic instruments are most useful (Hepburn 2006). The first occurs when the appropriate policy response varies between different firms or actors. In other words, if a market has a wide variety of different actor types to be influenced, the appropriate response for all of these different actors may vary. An economic signal affecting price or quantity will, however, send a uniform signal that will influence all actors in the market, despite their differences.

The second circumstance under which economic signals are most useful occurs when the regulator has imperfect information about the cost structure of firms or entities to be regulated (Hepburn 2006). In other words, if the governing entity has very good information about the costs of producing a good, a regulator might be able to put specific regulations on the industry to address the issue without imposing undue burden or cost. Without good information, however, the governing body would be unable to craft such targeted regulations and would be better off sending a clearer signal affecting price or quantity with an economic policy instrument.

Direct Price-Based Policy Instruments

Policy instruments directly changing prices intend to take the harm that an actor imposes on society and apply a tax, fee, or subsidy on the source of the harm equal to the magnitude of harm. Once marginal social costs (the total costs to society to produce a good) exceed the variable costs (the cost the firm bears), the difference is the external costs society must bear. Policy instruments that attempt to internalize these costs are known as marginal social costs pricing (Van Essen et al. 2008). A list of price-based economic instruments commonly seen in road transport literature is detailed in Table 6 (Elvik 1994, European Commission 2013, Hepburn 2006, Parry et al. 2007, Van Essen et al. 2008, Van Essen et al. 2012).

Table 6. Example Price-Based Economic Policy Instruments.

Fuel Taxes	**Congestion Charges**	**Vehicle Class Taxes**
Carbon taxes	Value added taxes	Vehicle age taxes
Distance-based taxes (VMT fees)	Insurance taxes	Vehicle value taxes
Fully differentiated VMT fees	Circulation taxes	Vehicle size and weight taxes
Registration fees	Vehicle sales taxes	Vehicle engine size taxes
Tolls	Parking fees	

If the tax or fee is not calculated equal to raise the price to the marginal social costs (or is incorrectly applied), it could cause perverse incentives—also known as unintended consequences—depending on how the policy errs. For example, if a tax is too high, it will provide too strong a signal, and the actors will produce less of the good than would be socially optimal. If the tax or fee is too low, the harm will continue undeterred (or only partially deterred). For these reasons, the tax, fee, or subsidy applied should be roughly equal to, and a good proxy for, the sources of the external costs.

Quantity-Based Economic Trading Instruments

This subcategory of economic instruments establishes a quantity-based control—like a ban or minimum or maximum production quantity limits—over a market (Hepburn 2006). These limits in turn send an implicit price signal to actors in the market to either reduce or increase consumption and/or production. Quantity controls can occur as either a purely economic instrument or as a regulatory instrument.

A common incarnation of a quantity-based economic instrument is through cap and trade, which functions by establishing a set maximum amount of a good a society can create and then allowing market participants to trade production credits. Such a system of credit trading creates a literal market for the regulated good, which indirectly establishes a minimum price for the good. If the governmental entity wishes to adjust the price level, it can issue or withhold credits in the market accordingly.

Quantity-based economic trading instruments are possible under a few constraints:

- The socially optimal allocation varies "greatly between different individuals and/or firms" (Hepburn 2006).
- The information needed to determine the socially optimal allocation is unavailable.

- The socially optimal aggregate quantity is known and fixed.

Variation in the socially optimal quantity across firms means that different firms or actors require different amounts of the good. For example, under a cap-and-trade system, some actors may be able to easily forgo using carbon, while others may incur significant expenses trying to alter production processes to eliminate carbon. Because of the cost variation within the market, a credit trading scheme will allow production credits to flow to those who value them most.

The second criterion means that the government would not be able to easily tell which actors in the market could use the good most efficiently or effectively. To extend the carbon metaphor, the government would not be able to tell which actors could easily or efficiently reduce their carbon use. As a result, a credit trading scheme would allow firms who most value carbon production credits to purchase them from firms that do not.

Knowing the socially optimal aggregate quantity allows the governmental entity to establish the target for the overall market (Hepburn 2006). For example, if the government knew that it wished to reduce carbon each year to achieve an eventual target reduction level, it could establish the maximum amount to be allocated each year in the market. Once licenses are allocated through the market and a compliance mechanism is established, a cap-and-trade scheme could take place.

Under these constraints, the formation of a cap-and-trade-style market ensures production credits end up with the actors who value them most. If the optimal quantity of a good is known and correctly implemented, in an ideal case, the market price for credits will equal the marginal social cost imposed on society, effectively internalizing the externality.

Non-economic Policy Instruments and Planning Activities

State and local agencies may also address transportation externalities through non-economic policy instruments that may work to mitigate the impact of negative externalities or promote positive externalities without working to internalize the cost of that externality. Non-economic policy instruments generally fall into two broad categories:

- Regulatory instruments and activities.
- Planning instruments and activities.

Regulatory Instruments

Regulatory instruments, also known as command-and-control instruments, require "firms or individuals to comply with specific standards, such as technology or performance standards" (Hepburn 2006). With these tools, governing bodies are able to affect behaviors or processes related to externalities by establishing or changing regulations directly, rather than relying on price signals to encourage actors to make the socially optimal choice.

Regulatory instruments are often implemented as command-and-control quantity-based controls but can take a variety of forms. For example, a requirement that all vehicles have safety equipment (e.g., seat belts) and a requirement that motorists use the safety equipment are regulatory quantity-based instruments. Some examples of regulatory requirements are included in Table 7 (Elvik 1994, European Commission 2013, Hepburn 2006, Parry et al. 2007, Van Essen et al. 2008, Van Essen et al. 2012).

Table 7. Example Regulatory Policy Instruments.

Require	Establish or Update	Implement/Increase Use
Collision insurance	Vehicle safety and cybersecurity standards	CV equipment
Pay-as-you-drive insurance	Vehicle performance standards	ITS
Safety equipment use	Rules of the road	Traffic management systems
Training or certification	License requirements	Public information campaign
Vehicle inspections	Quotas and targets	Law enforcement

The literature identifies a few criteria to help identify when regulatory instruments are useful (Hepburn 2006):

- The regulator has good information.
- The risk of government failure is low.
- The objective is best achieved by imposing similar requirements on different firms and individuals.

Good information implies that the regulator has sufficient knowledge about the industry to determine the optimal level of the regulated good. For example, the United States has determined that certain particulates and pollutants, such as lead, are unacceptable at any level. In this case, a regulator can easily determine that the socially optimal level of lead in gasoline is zero; the optimal policy would be an outright ban.

The risk of government failure is an important consideration since a regulation is only binding if it can be enforced. The government already regulated petroleum production, processing, and sale, so removing lead as a gasoline additive—for example—would be relatively easy and unlikely to fail.

The final criterion implies that, despite differences in the actors and firms in the market, the same standard or requirement will be effective. To continue with the example, despite the variety of actors in the market (e.g., manufacturers, distributors, and users), banning lead additives would be both appropriate and effective.

Formal regulatory activities within the transportation sector generally occur within one of four areas:

- Motor vehicle equipment.
- Motor vehicle operators.
- Structuring of rights and liabilities.
- Financing and contracting .

Additionally, state and local agencies may mitigate the impact of negative externalities or encourage positive externalities through service provision and the daily conduct of business.

For example, an agency in charge of operating a managed lane facility might adjust eligibility rules for free access in order to encourage certain user classes. Or, an agency might make changes in transit operations to accommodate new user groups.

Motor Vehicle Equipment

Although federal agencies such as NHTSA generally have preeminent authority in the setting of standards and requirements for motor vehicle equipment, states and local agencies are still able to exert some regulatory control over the design of vehicles. This is commonly accomplished by setting certain basic standards and regulations as a prerequisite for the legal operation of those vehicles on public infrastructure. State legislation, for example, may require vehicles to have braking systems, mirrors, and steering wheels that allow the driver to control the vehicle. Agencies may also prohibit modifications or additional equipment that may make the vehicle unsafe to operate (Douma and Fatehi 2016). These mandates and requirements may be enforced through state and local vehicle registration and safety inspection programs, or through visual inspection during roadside law enforcement.

Motor Vehicle Operators

States and local agencies are responsible for determining who is eligible to drive on public infrastructure and the responsibilities associated with driving. Therefore, all states require drivers to have a valid government-issued license in order to operate a motor vehicle. Licensing is a regulatory instrument that is used to ensure that all drivers have some baseline knowledge of vehicle operation. Licenses also typically come with requirements about who can obtain a license, such as age and ability to see (Douma and Fatehi 2016). Rules and laws regarding on-road responsibilities, such as yielding the right-of-way, not operating commercial vehicles in inside lanes, and not driving while distracted, also function as a regulation on motor vehicle operator behavior.

In addition to legal requirements for the licensing of drivers, common legal requirements regarding motor vehicle operators include the following (Douma and Fatehi 2016):

- Regulations about leaving vehicles unattended.
- Requirements for operator behavior in the event of a traffic accident, road construction, funeral processions, and other roadway events.
- Requirements for driver attentiveness to various warnings and signage.
- Requirements for safe driving (e.g., keeping hands on the steering wheel, not having an obstructed view, and using seatbelts).
- Definitions of and prohibitions on reckless, distracted, and negligent driving.
- Requirements about safe following distance.

Structuring of Rights and Liabilities

Agencies may, if they have the authority, restructure civil and criminal liabilities in order to shift risk and alter producer and/or consumer behavior. One method for addressing the issue of risk associated with driving is requiring vehicular liability insurance by drivers. The states of Nevada, Florida, and California currently have specific insurance requirements for the testing of AV systems. The current structure of the insurance market may be changed significantly if AVs and CVs do, in fact, reduce vehicular crashes. Researchers have posited that liability for vehicular incidents may ultimately shift from the driver to the auto manufacturer (Douma and Fatehi 2016).

Financing and Contracting

In some cases it may be that a private-sector market for a good or service does not exist or cannot exist absent government intervention. In these cases, a transportation agency may establish the market itself or work in partnership with the private sector in order to establish the necessary environment for the market to flourish. State and local agencies are also generally free to enter into an array of public-private partnerships in order to provide enhanced transportation services. States may need to pass enabling legislation in order to facilitate these partnerships.

Current State Regulation of AVs

As automakers and technology companies develop and test AV and CV technologies, policy makers and government agencies in some states have started to regulate their activities. Most of these regulations focus on AVs for testing purposes, with only a few addressing the operation of AVs outside of a testing environment. Nevada was the first state to pass legislation creating regulations on AVs, and several states quickly followed their lead. Four states (California, Florida, Nevada, and Michigan) and Washington, D.C., have passed legislation regarding testing and/or operation of automated vehicles on public roads, while Georgia and North Dakota have legislatively directed studies of AV technology. Tennessee has enacted legislation prohibiting its local governments from banning the use of AVs.

As with most state regulation on vehicle systems and vehicle operators, the primary objective of recent AV legislation is increasing safety. Therefore, regulations typically require that entities testing vehicles in the state abide by some set of rules selected to increase safety of any testing activities. States thus require items such as registering test vehicles, reporting problems during testing, ensuring drivers are adequately trained, and so forth. Current regulation of AV testing has thus far aligned with traditional transportation system regulation in that it is targeted at (Wagner 2015):

- Vehicle components.
- Operational requirements.
- Operator requirements.
- Vehicle conversion and liability requirements.
- Mobile communications and data privacy requirements.

Regarding vehicle components in AVs, several states require that AVs have a mechanism that allows an operator to disengage the autonomous technology, a visual indicator that informs whether the technology is enabled, and a function to alert the operator if the technology system fails.

Planning Activities

Aside from the traditional tools economists recommend to internalize externalities, there are planning activities that may be deployed in anticipation of or in response to transportation issues like externalities. Broadly, transportation planning is an ongoing, iterative process that informs decisions about policies, programs, and investments that are made for the transportation system. It includes goal setting, analysis of alternative strategies and scenarios, implementation of programs and projects, evaluation and monitoring, and public engagement (U.S. Department of Transportation 2013).

Planning activities in general are undertaken to assist states, regions, and communities in achieving their vision and goals for the future (Federal Highway Administration 2015). Through the planning process, transportation agencies work with partners and the public to identify short- and long-term transportation investments and programs that contribute to achieving their shared vision. Many of these activities are not generally implemented with the objective of achieving one specific goal or objective, such as internalizing a transportation externality. Rather, the impact of externalities and the desire to promote or mitigate (as appropriate) that impact will be incorporated into broader regional goals and objectives, such as congestion mitigation, increased safety, and air quality improvement. For example, regions undertake a congestion management process (CMP) that evaluates the potential of different strategies to manage congestion. However, the CMP is not a "standalone process but instead should be integrated into the larger overall planning process" (Federal Highway Administration 2015). Furthermore, congestion plans will not address the specific congestion externalities caused by AV or CV adoption in a vacuum—they will be viewed alongside existing causes of and strategies to address congestion.

Other specific activities throughout the planning process may contribute more directly to enabling or encouraging the private-sector actions that were identified in Task 2. The planning process can be broken down into a framework with five stages (U.S. Department of Transportation 2013):

- Strategic direction.
- Planning analysis.
- Program selection.
- Evaluation and monitoring.
- Education and outreach.

Each stage involves different activities that may be used to internalize the externalities associated with the impacts of CV/AV technology on the transportation system. This section discusses each stage and the types of activities that are involved during each stage.

Strategic Direction

The planning process begins with the identification of a strategic direction, or a vision, for a community or region's transportation future. This process includes:

- Goals that address key desired outcomes.
- Objectives that support the achievement of goals through specific, measurable statements.
- Performance measures that track progress and allow for comparison among alternative policy and investment strategies. The achievement of goals and objectives is defined by the performance measures.

The strategic direction stage establishes a high-level framework for the rest of the planning process. Transportation agencies may want to consider AV and CV technologies in terms of how these technologies contribute to broad agency goals, but this visioning process is not designed to directly affect private-sector actions. This stage of the planning process can help identify criteria by which to measure future planning activities that may internalize the externalities of CV and AV technology. Strategic planning activities to be undertaken at a high level may include:

- Identify goals and objectives that may be achieved through AV and CV technologies.
- Develop performance measures that support specific safety, congestion, mobility, and environmental goals that may be supported by AV and CV systems and can be used to track the results of investment in these systems over time.
- Serve as a leader in CV and AV deployment by helping to build the business case for investing in CVs, generating support for adoption of safety and mobility applications, and promoting incentives for producers to improve applications and technology.

Planning Analysis

Transportation agencies conduct analyses to compare and develop a set of policy and investment priorities. The research undertaken in this stage of the planning process will be used to identify strategy packages that support goals and objectives, consider the trade-offs among different policy priorities, and feed into short- and long-range transportation plans (U.S. Department of Transportation 2013). Planners will have to integrate CV/AV trends and targets into travel modeling, forecasting, scenario analyses, and other tools currently used to inform long-term planning, development of the Transportation Investment Plans (TIP)/Statewide Transportation Investment Plan (STIP), and planning work plans (Krechmer et al. 2015). In order to include AV and CV technologies in planning analysis, agencies may:

- Collect baseline data on past trends, existing strategies, available funding, and other constraints to CV/AV deployment.
- Identify targets that can be used to compare and prioritize AV and CV technologies' performance.

These steps would contribute broadly to internalizing the externalities associated with CVs and AVs by incorporating them into the process by which transportation agencies identify trends and prioritize policies, investments, and programs.

Program Selection

Programming is the stage in which agencies select the specific investments and programs to include in plans such as the TIP or STIP. Program selection is based on the ability of candidate programs to support specific performance targets or achieve desired trends as identified in previous planning stages.

By providing or investing in particular services, an agency can change how it provides its current range of transportation services. For example, an agency in charge of operating a managed lane facility might adjust eligibility rules for free access in order to encourage certain user classes. Or, an agency might make changes in transit operations to accommodate new user groups. In some cases it may be that a private-sector market for a good or service does not exist or cannot exist absent government intervention. In these cases, it may be desirable for a transportation agency to establish the market itself or work in partnership with the private sector in order to establish the necessary environment for the market to flourish (adapted from Bardach 2005).

Evaluation and Monitoring

As an iterative process, transportation planning should evaluate, monitor, and report on the activities and implementation of programs on an ongoing basis. The results of evaluation can also be used to assess specific policies that are implemented to address externalities for their ability to achieve the desired outcomes. For example, transportation agencies may evaluate whether a carbon tax has actually contributed to consumer purchases of AVs that are lower polluting. The results can be used to inform investment decisions, public information campaigns, and decisions about other policy actions and instruments. Evaluation activities that may inform programming decisions and public education campaigns include:

- Ensure AV/CV-related policies and planning activities align with transportation goals and existing plans.
- Evaluate and identify ways to incorporate AV/CV technologies into existing programming.
- Monitor pilot projects and deployments.
- Conduct analysis to understand the extent to which implemented strategies have been effective at achieving goals (Krechmer et al. 2015).

Education and Outreach

Public involvement and education are used to inform the planning process and should be integrated throughout. This step is also a planning activity that can have a direct influence on the behavior of consumers and producers in the market. In general, as AV and CV technology is developed and deployed, new information should be relayed to the public to expand their understanding of the technologies.

Transportation agencies may, through any number of mediums and strategies, provide information to consumers as a means of encouraging desired behavior. For example, to encourage consumers to purchase CVs with safety, mobility, or environmental applications, transportation agencies can report and communicate the various benefits that have been identified through analysis and evaluation.

Agencies may also coordinate with departments of transportation, metropolitan planning organizations, other rural and regional planning organizations, transit agencies, and other stakeholders. For example, they can report information about AV/CV system performance and the effectiveness of plans and programs. They can also coordinate and form partnerships with the private sector to speed commercialization of CV technologies.

In addition to those policy instruments that were identified as being particularly effective at internalizing externalities (taxes, fees, subsidies, and regulations), researchers identified three classes of planning activities that have the most direct influence on consumer and producer actions. A transportation agency might undertake these planning activities to sustain and encourage positive externalities and/or mitigate the impact of negative externalities. Examples of such activities are summarized in Table 8.

Table 8. Example Planning Activities.

Analysis and Evaluation	Provide or Invest In	Educate or Inform
Scenario planning	Infrastructure	Publicize
Study	Vehicles or transit	Communicate
Collect data	Job and skills training	Inform
Performance measures	Research and development	Collaborate

Alignment of Policy Instruments with Producer and Consumer Actions

As part of Task 2, the research team identified externalities associated with the deployment of AV and CV systems and identified actions that may be undertaken by producers and consumers of AV and CV products and services to internalize those externalities. The research team used several analytical steps to aid in identifying and matching policy instruments to externality actions.

Test against Heuristics

When assessing external actions, the team first tested them against several heuristics derived from microeconomic and public policy literature. Following these tests, the team considered each external action individually to ensure that appropriate policy actions were identified.

Heuristic 1: If You Want More of Something, Make It Less Expensive

Microeconomic theory says that when the price of a good decreases, all things being equal, demand for the good will increase as well. The traditionally recommended solution when there is a positive externality (an actor not doing something positive) is to provide a subsidy, thereby making it less expensive and increasing demand for the good. For example, subsidizing fuel-efficient vehicles will decrease their cost and increase demand.

Some other quantity-based policy instruments can also make goods less expensive; increasing the quantity of a good in the market will, all things being equal, decrease price and increase demand. For example, requiring a company to produce more of something (e.g., fuel-efficient vehicles) through a quantity-based regulation could also work. When assessing external actions where an individual needs encouragement, the research team would first try to find ways to decrease the price.

Heuristic 2: If You Want Less of Something, Make It More Expensive

The inverse of the previous rule is also true: when the price of a good increases, all things being equal, demand for the good will decrease. The traditionally recommended action when there is a negative externality (an actor doing too much of something) is to increase the price through a tax, thus decreasing demand for the good. For example, taxing VMT provides a price signal that encourages motorists to drive less.

Similar to the previous heuristic, other policies can work to discourage an activity by making it more expensive. Using a regulatory power to cap the quantity of a good supplied to the market will, all things being equal, increase price and decrease demand. For example, under a cap-and-trade system, a limit on the amount of carbon production and the establishment of market-to-trade permits will result in the price of carbon increasing and demand decreasing.

Heuristic 3: Use Proportional and Precisely Targeted Policies

When discouraging a negative externality or encouraging a positive externality, policies that affect prices (e.g., taxes or subsidies) should approximate and be a good proxy for the marginal external social costs. If these incentives are inappropriately applied or calculated, the policy will likely cause unintended consequences. For example, if a tax is too high, it will provide too strong a signal, and the actors will produce less of the good than would be socially optimal. If the tax or fee is too low, the harm will continue undeterred (or only partially deterred).

In practice, when reviewing externality actions, the research team would try to recommend pricing policies that align well with the appropriate activity. When trying to discourage excessive driving, for example, a VMT tax calculated to match the marginal external cost of each additional mile traveled would both discourage the correct activity and appropriately match the external costs.

Identify Other Possible Policy Instruments

Second, the research team assessed each externality action individually to identify any other possible policy instruments that could encourage or discourage an activity. The process involved the following steps:

- Identify the source of the externality action (i.e., who is causing the harm).

- Assess if the externality action needs encouragement or discouragement.
- Identify existing policy instruments that could be applied or changed.
- Review policy instrument categories to identify any overlooked instruments.

Consider Other Actions

Finally, in addition to those policy instruments that were identified as being particularly effective at internalizing externalities (taxes, fees, subsidies, and regulations), there are also a number of actions a transportation agency might undertake to sustain and encourage positive externalities and/or mitigate the impact of negative externalities. These activities include:

- **Structure of private rights (adapted from Bardach [2005]):** Agencies may, if they have the authority, restructure civil and criminal liabilities in order to shift risk and alter producer and/or consumer behavior.
- **Service provision:** This family of policy instruments generally refers to changes in how a transportation agency provides its current range of transportation services. For example, an agency in charge of operating a managed-lane facility might adjust eligibility rules for free access in order to encourage certain user classes. Or, an agency might make changes in transit operations to accommodate new user groups.
- **Information/education:** Transportation agencies may, through any number of mediums and strategies, provide information to consumers as a means of encouraging desired behavior.
- **Financing/contracting/collaboration (adapted from Bardach [2005]):** In some cases, a private-sector market for a good or service may not exist or cannot exist absent government intervention. In these cases, it may be desirable for a transportation agency to establish the market itself or work in partnership with the private sector to establish the necessary environment for the market to flourish.

Results of Analysis

Tables 9 through 13 present the results of the analysis. Each table shows the various economic and regulatory instruments that may be deployed to facilitate the various consumer and producer actions associated with each externality. Economic instruments include taxes, subsidies, and quotas/targets. Regulatory activities include the following:

- Mandates on vehicle equipment.
- Mandates on operator behavior.
- Structure of private rights.
- Service provision.
- Information provision.
- Financing and contracting.

General planning activities in response to AV/CV implementation are assumed to occur regardless of the specific desired action of producers and consumers. These activities include strategic direction, planning analysis, programming, evaluation, and monitoring.

Table 9. Policy Instruments to Address Traffic Crashes Externality.

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell safe AVs	On AVs that do not meet the desired safety specifica-tions, standards, guidelines, etc.	To purchasers of AVs that meet the desired safety specifica-tions, standards, and guidelines To AV producers to stimulate the production of AVs that meet the desired safety specifica-tions, standards, and guidelines	Establish-ment of production targets (with associated financial incentives) for vehicles with the desired safety specifica-tions, standards, and guidelines	Establish basic safety require-ments about prerequisite to government registration and/or licensing of vehicles		Restructuring of liability for vehicle producers in the event of safety failures Restructuring of liability and insurance require-ments for the drivers of vehicles with the desired safety specifica-tions, standards, and guidelines	Expedited and/or privileged access to existing services for vehicles with the desired safety specifica-tions, standards, and guidelines		Public-private partnerships for the development of infra-structure that will support AV safety applications

Table 9. Policy Instruments to Address Traffic Crashes Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure safe operations (across different use cases/operating conditions)		To producers to act in an appropriate and timely manner in response to communica-tions with road operators		Require disclosure by AV producers of data require-ments necessary to ensure safe Level 4 and 5 operation		Restructuring of liabilities for AV producers that do not act upon communica-tions with road operators	Make transporta-tion data (e.g., asset status and condition) open and available for use by developers Standardize and modernize data-based transporta-tion systems (including ITS and asset management data systems)		Public-private partnerships to establish the required technical infra-structure and data-sharing capabilities to support communica-tions between AV producers and road operators

Table 9. Policy Instruments to Address Traffic Crashes Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase vehicles with V2V/V2I capabilities	On non-V2V/V2I-capable vehicles (sales, vehicle registration, etc.)	To purchasers of V2V/V2I-capable vehicles (tax refund and rebates)		Establish V2V/V2I require-ments as prerequisite to government registration and/or licensing		Restructuring of civil and criminal liabilities for users of V2V/V2I services	Establish CV infra-structure and provide associated safety services Provide expedited and/or privileged access to existing services for V2V/V2I-capable vehicles (e.g., managed lanes, signal priority, and parking access)	Public information campaign on the benefits of V2V/V2I capabilities	Private-sector partnerships to establish required CV infra-structure and develop the market Subsidized loans for V2V/V2I-capable vehicle purchases

Table 9. Policy Instruments to Address Traffic Crashes Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase and use aftermarket V2V safety applications		To purchasers of V2V safety applications (tax refund, tax discount, and rebates)		Establish basic safety require-ments as prerequisite to government registration and/or licensing		Restructuring of civil and criminal liabilities for users of V2V safety applications	Establish CV infra-structure and provide associated safety services Provide expedited access to existing premium services (e.g., managed lanes, signal priority, and parking access) for vehicles equipped with V2V safety applications	Public information campaign on the benefits of V2V safety applications	Private-sector partnerships to establish required CV infra-structure and develop the market Subsidized loans for V2V safety application purchases

Table 9. Policy Instruments to Address Traffic Crashes Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers are attentive to V2V and V2I safety warnings in vehicles				Establish basic safety require-ments/ standards as prerequisite to government registration and/or licensing	Establish and codify basic operator respon-sibilities for V2V/V2I-equipped vehicles for use in roadside law enforcement	Restructuring of civil and criminal liabilities for users who are not attentive to V2V and V2I warnings		Public information campaign regarding V2V and V2I safety warnings	
Consumers purchase safe AVs	On AVs (sales, vehicle registration, etc.) that do not meet desired safety levels	To purchasers of AVs with the desired level of safety		Establish basic safety require-ments and desired safety standards/ specifica-tions/etc. as a prerequisite to government registration and/or licensing	Establish and codify basic AV operator respon-sibilities	Restructuring of civil and criminal liabilities for users of AVs that meet the desired safety thresholds	Expedited and/or privileged access to existing services for safe AVs (e.g., managed lanes, signal priority, and parking access)	Public information campaign on the benefits of safe AVs	Subsidized loans for safe AV purchases

Table 9. Policy Instruments to Address Traffic Crashes Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers follow safe AV maintenance and operating procedures					Establish and codify basic operator respon-sibilities for V2V/V2I-equipped vehicles for use in roadside law enforcement Establish and codify basic owner/ operator maintenance respon-sibilities as part of government licensing and/or registration				

Table 10. Policy Instruments to Address Congestion Externality.

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell interoperable V2V or V2I mobility applications		For the development and sale of inter-operable V2V or V2I mobility applications		Establish require-ments for inter-operable V2V or V2I applications for use in government registration and/or licensing Establish and codify basic operating require-ments/ standards for V2V and V2I inter-operability					Private-sector partnerships to establish required CV infra-structure and develop the market for V2V and V2I mobility applications

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell safe AVs	On AVs that do not meet the desired safety specifica-tions, standards, guidelines, etc.	To purchasers of AVs that meet the desired safety specifica-tions, standards, and guidelines To AV producers to stimulate the production of AVs that meet the desired safety specifica-tions, standards, and guidelines	Establish-ment of production targets (with associated financial incentives) for vehicles with the desired safety specifica-tions, standards, and guidelines	Establish basic safety require-ments as prerequisite to government registration and/or licensing of vehicles		Restructur-ing of liability for vehicle producers in the event of safety failures Restructur-ing of liability and insurance require-ments for the drivers of vehicles with the desired safety specifica-tions, standards, and guidelines	Expedited and/or privileged access to existing services for vehicles with the desired safety specifica-tions, standards, and guidelines		Public-private partnerships for the development of infra-structure that will support AV safety applications

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell connected AVs that harmonize traffic flow	On vehicles that do not feature traffic flow harmoniza-tion	To producers for the development and sale of AVs featuring traffic flow harmoniza-tion capabilities		Establish basic require-ments for traffic flow harmoniza-tion features in AVs as part of vehicle registration			Develop or expand intelligent transporta-tion systems capable of supporting traffic flow harmoniza-tion		Public-private partnerships to facilitate the develop-ment, operation, and maintenance of required technology infra-structure to support traffic flow harmoniza-tion

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency and safe operations (across different use cases/operating conditions)		To producers to act in an appropriate and timely manner in response to communications with road operators		Require disclosure by AV producers of data requirements necessary to ensure safe Level 4 and 5 operation		Restructuring of liabilities for AV producers that do not act upon communications with road operators	Make transportation data (e.g., asset status and condition) open and available for use by developers Standardize and modernize data-based transportation systems (including ITS and asset management data systems)		Public-private partnerships to establish the required technical infrastructure and data-sharing capabilities to support communications between AV producers and road operators

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Private shared-vehicle services operate SAV		To shared-vehicle service and/or transit providers for the purchase of SAVs To shared-vehicle services to provide SAV-related services			Establish and codify operator respon-sibilities in SAV environment		Make data on system operations available to SAV operators and applications developers		Develop public-private partnerships with SAV service providers to develop the SAV market

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Private shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit		Offered to private shared-vehicle services to promote the prioritization of ridesharing and linkages with line-haul mass transit					Orient transit operations to better complement shared-vehicle services Make data on transit operations available to shared-vehicle services and applications developers Expedited or privileged access to existing facilities (e.g., bus lanes, managed lanes, and signal priority) for private shared-vehicle services that prioritize ridesharing and linkages with line-haul mass transit	Public information campaign to educate the public on how transit and ridesharing can complement one another	Develop public-private partnerships between transit providers and private-vehicle service providers for the sharing of data and coordination of operations

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	**Subsidies and Grants**	**Quotas or Targets**	**Mandates on Vehicle Equipment**	**Mandates on Operator Behavior**	**Structure of Private Rights**	**Service Provision**	**Information Provision**	**Financing and Contracting**
Consumers purchase vehicles with V2V/V2I capabilities	On non-V2V/V2I-capable vehicles (sales, vehicle registration, etc.)	To purchasers of V2V/V2I-capable vehicles (tax refund and rebates)		Establish V2V/V2I require-ments as prerequisite to government registration and/or licensing		Restructur-ing of civil and criminal liabilities for users of V2V/V2I services	Establish CV infra-structure and provide associated safety services Expedited and/or privileged access to existing services for V2V/V2I-capable vehicles (e.g., managed lanes, signal priority, and parking access)	Public information campaign on the benefits of V2V/V2I capabilities	Private-sector partnerships to establish required CV infra-structure and develop the market Subsidized loans for V2V/V2I-capable vehicle purchases

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase and use aftermarket V2V safety applications		To purchasers of V2V safety applications (tax refund, tax discount, and rebates)		Establish basic safety require-ments as prerequisite to government registration and/or licensing		Restructur-ing of civil and criminal liabilities for users of V2V safety applications	Establish CV infra-structure and provide associated safety services Provide expedited access to existing premium services (e.g., managed lanes, signal priority, and parking access) for vehicles equipped with V2V safety applications	Public information campaign on the benefits of V2V safety applications	Private-sector partnerships to establish required CV infra-structure and develop the market Subsidized loans for V2V safety applications purchases

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers use V2V/V2I mobility applications		To purchasers of V2V/V2I mobility applications (tax refund, tax discount, and rebates)					Establish CV infra-structure and provide associated safety, environ-mental, and mobility services Provide expedited access to existing premium services (e.g., managed lanes, signal priority, and parking access) for vehicles equipped with V2V/V2I mobility applications	Public information campaign on the benefits of V2V mobility applications	Private-sector partnerships to establish required CV infra-structure and develop the market for V2V and V2I mobility applications Subsidized loans for V2V mobility applications purchases

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers are attentive to V2V and V2I safety and mobility messages in vehicles					Establish and codify basic operator respon-sibilities for V2V and V2I-equipped vehicles for use in roadside law enforcement			Public information campaign regarding V2V and V2I mobility warnings	
Consumers purchase safe AVs	On AVs (sales, vehicle registration, etc.) that do not meet desired safety levels	To purchasers of AVs with the desired level of safety		Establish basic safety require-ments and desired safety standards/ specifica-tions/etc. as a prerequisite to government registration	Establish and codify basic AV operator respon-sibilities	Restructur-ing of civil and criminal liabilities for users of AVs that meet the desired safety thresholds	Expedited and/or privileged access to existing services for safe AVs (e.g., managed lanes, signal priority, and parking access)	Public information campaign on the benefits of safe AVs	Subsidized loans for safe AV purchases

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers follow safe AV maintenance and operating procedures					Establish and codify basic operator respon-sibilities for V2V and V2I-equipped vehicles for use in roadside law enforcement Establish and codify basic owner/ operator maintenance respon-sibilities as part of government licensing and/or registration				

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase connected AVs that harmonize traffic flow	On vehicles that do not feature traffic flow harmoniza-tion	To consumers for the purchase of AVs capable of harmonizing traffic flow		Establish basic require-ments for traffic flow harmoniza-tion features in AVs as part of vehicle registration			Develop or expand intelligent transporta-tion systems capable of supporting traffic flow harmoniza-tion Expedited and/or privileged access to existing services (e.g., managed lanes, signal priority, and parking access) for traffic flow harmonizing AVs	Public information campaign on the benefits of traffic flow harmoniza-tion	Public-private partnerships to develop, operate, and/or maintain the required technology infra-structure to support traffic flow harmoniza-tion
Consumers of AVs minimize VMT growth, though technology reduces the non-monetary costs of driving	Implement a road user charge Implement regional tolling						Expand existing tolling		

Table 10. Policy Instruments to Address Congestion Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers of AVs do not drive farther for housing, even though the technology decreases travel cost	Implement a distance-based road user charge	Offered to home buyers/ renters to live in preferred development (e.g., through location-efficient mortgage subsidies)				Modify existing zoning and develop-ment regulations in anticipation of potential travel impacts			
Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth	To private vehicle owners that are not part of a SAV system	To consumers to use SAV systems To SAV system owners/ operators for expansion of services			Establish and codify operator respon-sibilities in SAV environment			Public information campaign regarding the benefits of SAV systems	Private-sector partnerships to establish and expand the market for SAV systems

Table 11. Policy Instruments to Address Pollution Externality.

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell interoperable V2V or V2I environmental and mobility applications		For the development and sale of inter-operable V2V or V2I environ-mental and mobility applications		Establish require-ments for inter-operable V2V or V2I applications for use in government registration and/or licensing Establish and codify basic operating require-ments/ standards for V2V and V2I inter-operability					Private-sector partnerships to establish required CV infra-structure and develop the market for V2V and V2I environ-mental mobility applications

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency and safe operations (across different use cases/operating conditions)		To producers to act in an appropriate and timely manner in response to communications with road operators		Require disclosure by AV producers of data requirements necessary to ensure safe Level 4 and 5 operation		Restructuring of liabilities for AV producers that do not act upon communications with road operators	Make transportation data (e.g., asset status and condition) open and available for use by developers Standardize and modernize data-based transportation systems (including ITS and asset management data systems)		Public-private partnerships to establish the required technical infrastructure and data-sharing capabilities to support communications between AV producers and road operators
Producers develop and sell AVs that are lower polluting		For the development of lower-polluting AVs For the sale of lower-polluting AVs	Establish output quotas for lower-polluting vehicles	Establish basic configuration standards (e.g., size, emissions rating, and fuel source) for use in registration					

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell AVs with eco-driving operating objectives		For the development of AVs with eco-driving operating objectives For the sale of AVs with eco-driving operating objectives		Establish require-ments for AVs with eco-driving operating objectives for use in government registration and/or licensing					
Consumers purchase vehicles with V2V/V2I capabilities	On non-V2V/V2I-capable vehicles	For the purchase of V2V/V2I-capable vehicles				Restructure insurance require-ments for purchasers of V2V/V2I-capable vehicles	Develop required technology infra-structure for the provision of V2V/V2I services	Public information campaign on the benefits of V2V/V2I systems	Public-private partnerships to develop the required technology infra-structure for the provision of V2V/V2I services
Consumers purchase aftermarket V2V safety applications		Provided to purchasers of V2V safety applications (tax refund, tax discount, and rebates)							

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers use V2V/V2I environmental, mobility, and safety applications		To purchasers of V2V/V2I environ-mental, mobility, and safety applications (tax refund, tax discount, and rebates)					Establish CV infra-structure and provide associated safety, environ-mental, and mobility services Provide expedited access to existing premium services (e.g., managed lanes, signal priority, and parking access) for vehicles equipped with V2V/V2I environ-mental, mobility, and safety applications	Public information campaign on the benefits of V2V/V2I environ-mental, mobility, and safety applications	Private-sector partnerships to establish required CV infra-structure and develop the market for V2V and V2I environ-mental, mobility, and safety applications Subsidized loans for V2V/V2I environ-mental, mobility, and safety application purchases

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers are attentive to in-vehicle V2V and V2I environmental, mobility, and safety messages					Establish and codify basic operator respon-sibilities for V2V/V2I-equipped vehicles for use in roadside law enforcement			Public information campaign regarding V2V and V2I environ-mental, mobility, and safety warnings	
Private shared-vehicle services operate SAVs		To shared-vehicle service and/or transit providers for the purchase of SAVs To shared-vehicle services to provide SAV-related services			Establish and codify operator respon-sibilities in SAV environment		Make data on system operations available to SAV operators and applications developers		Develop public-private partnerships with SAV service providers to develop the SAV market

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
SAV operators prioritize ridesharing and linkages with line-haul mass transit		Offered to SAV operators to promote the prioritization of ridesharing and linkages with line-haul mass transit					Orient transit operations to better complement SAV systems Make data on transit operations available to SAV operators and applications developers Expedited or privileged access to existing facilities (e.g., bus lanes, managed lanes, and signal priority) for shared transit systems that prioritize ridesharing and linkages with line-haul mass transit	Public information campaign to educate the public on how transit and ridesharing can complement one another	Develop public-private partnerships between transit providers and SAV operators for the sharing of data and coordination of operations

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Developers build fewer parking facilities or build parking facilities that can be adapted to other purposes	On the development of parking facilities	Directed to the developers of facilities that can be adapted to other purposes				Modify existing zoning and development regulations to discourage development of undesirable facilities Modify existing zoning and development regulations to encourage the development of parking facilities that can be adapted to other purposes	Modify municipal parking services to reduce demand for traditional parking facilities or increase demand for parking facilities that can be adapted to other purposes		Public-private partnerships for the development of multi-purpose parking facilities Subsidized loans for the development of multi-purpose parking facilities

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase AVs that are lower polluting	On AVs (sales, vehicle registration, etc.) levied on vehicles that are not lower polluting Local option fuel tax, emissions tax, carbon tax, or other emissions and/or fuel consumption –based user fee	To purchasers of AVs with vehicles that are lower polluting		Establish basic require-ments and desired standards/ specifica-tions/etc. with regard to pollution as a prerequisite to government registration			Expedited and/or privileged access to existing services (e.g., managed lanes, signal priority, and parking access) for vehicles that are lower polluting	Public information campaign regarding the impact of low-polluting vehicles on air quality	Subsidized loans for the purchase of lower-polluting AVs

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers purchase AVs with eco-driving operating objectives	On AVs (sales, vehicle registration, etc.) levied on vehicles that lack eco-driving operating objectives Local option fuel tax, emissions tax, carbon tax, or other emissions and/or fuel consumption –based user fee	To purchasers of AVs with vehicles with eco-driving operating objectives		Establish basic environmental requirements and desired standards/ specifications/etc. as a prerequisite to government registration and/or licensing			Expedited and/or privileged access to existing services (e.g., managed lanes, signal priority, and parking access) for vehicles eco-driving operating objectives	Public information campaign regarding the impact of eco-driving operation on vehicular performance and associated transportation system impacts (specifically environmental impacts)	Subsidized loans for the purchase of AVs with eco-driving operating objectives
Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth	To private vehicle owners that are not part of a SAV system	To consumers to use SAV systems To SAV system owners/ operators for expansion of services			Establish and codify operator responsibilities in SAV environment			Public information campaign regarding the benefits of SAV systems	Private-sector partnerships to establish and expand the market for SAV systems

Table 11. Policy Instruments to Address Pollution Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers of AVs minimize VMT growth though the technology decreases travel cost and enables mobility among some who cannot otherwise drive	Implement a distance-based road user charge Implement regional tolling						Expand tolling and pricing on regional network		
Consumers of AVs do not drive farther for housing even though the technology decreases travel cost	Implement a distance-based road user charge	Offered to home buyers/ renters to live in preferred development (e.g., through location-efficient mortgage subsidies)				Modify existing zoning and development regulations in anticipation of potential travel impacts			

Table 12. Policy Instruments to Address Land Development Externality.

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth	To private vehicle owners that are not part of a SAV system	To consumers to use SAV systems To SAV system owners/ operators for expansion of services			Establish and codify operator respon-sibilities in SAV environment			Public information campaign regarding the benefits of SAV systems	Private-sector partnerships to establish and expand the market for SAV systems

Table 12. Policy Instruments to Address Land Development Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
SAV operators prioritize ridesharing and linkages with line-haul mass transit		Offered to SAV operators to promote the prioritization of ridesharing and linkages with line-haul mass transit					Orient transit operations to better complement SAV systems Make data on transit operations available to SAV operators and applications developers Expedited or privileged access to existing facilities (e.g., bus lanes, managed lanes, and signal priority) for shared transit systems that prioritize ridesharing and linkages with line-haul mass transit	Public information campaign to educate the public on how transit and ridesharing can complement one another	Develop public-private partnerships between transit providers and SAV operators for the sharing of data and coordination of operations

Table 12. Policy Instruments to Address Land Development Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers use Level 5 vehicles to avoid parking in urban centers	Increase parking fees in urban centers Implement congestion-pricing-based fee schedules for parking facilities	On travel into urban centers by users of Level 5 vehicles where the vehicle was not parked	Adjust municipal regulations regarding parking to discourage parking in urban centers (e.g., reducing the time a vehicle may be parked in an on-street space)				Adjust the amount of available municipal parking space		

Table 12. Policy Instruments to Address Land Development Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Developers build fewer parking facilities, or build parking facilities that can be adapted to other purposes	On the development of parking facilities	Directed to the developers of facilities that can be adapted to other purposes	Modify existing zoning and development regulations to discourage development of undesirable facilities Modify existing zoning and development regulations to encourage the development of parking facilities that can be adapted to other purposes				Modify municipal parking services to reduce demand for traditional parking facilities or increase demand for parking facilities that can be adapted to other purposes		Public-private partnerships for the development of multi-purpose parking facilities Subsidized loans for the development of multi-purpose parking facilities

Table 12. Policy Instruments to Address Land Development Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth	To private vehicle owners that are not part of a SAV system	To consumers to use SAV systems To SAV system owners/ operators for expansion of services			Establish and codify operator respon- sibilities in SAV environment			Public information campaign regarding the benefits of SAV systems	Private-sector partnerships to establish and expand the market for SAV systems

Table 12. Policy Instruments to Address Land Development Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
SAV operators prioritize ridesharing and linkages with line-haul mass transit		Offered to SAV operators to promote the prioritization of ridesharing and linkages with line-haul mass transit					Orient transit operations to better complement SAV systems Make data on transit operations available to SAV operators and applications developers Expedited or privileged access to existing facilities (e.g., bus lanes, managed lanes, and signal priority) for shared transit systems that prioritize ridesharing and linkages with line-haul mass transit	Public information campaign to educate the public on how transit and ridesharing can complement one another	Develop public-private partnerships between transit providers and SAV operators for the sharing of data and coordination of operations

Table 13. Policy Instruments to Address Mobility Externality.

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Producers develop and sell Level 5 vehicles that are usable by aging adults and individuals with disabilities		For the development of Level 5 vehicles that are usable by aging adults and individuals with disabilities For the sale of Level 5 vehicles that are usable by aging adults and individuals with disabilities		Establish require-ments for Level 5 vehicles that are usable by aging adults and individuals with disabilities for use in government registration and/or licensing					

Table 13. Policy Instruments to Address Mobility Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Private shared-vehicle services purchase and operate SAVs		To shared-vehicle service and/or transit providers for the purchase of SAVs To shared-vehicle services to provide SAV-related services			Establish and codify operator respon-sibilities in SAV environment		Make data on system operations available to SAV operators and applications developers		Develop public-private partnerships with SAV service providers to develop the SAV market
Aging adults and individuals with disabilities (consumers) purchase Level 5 AVs		To aging adults and individuals with disabilities to purchase Level 5 vehicles					Expanded access to existing services for aging adults and individuals with disabilities who are using Level 5 vehicles	Public information campaign targeted to aging adults and individuals with disabilities regarding the benefits of safe AVs	Subsidized loans to aging adults and individuals with disabilities to purchase Level 5 vehicles

Table 13. Policy Instruments to Address Mobility Externality (Continued).

Actions of Producers and Consumers	Economic Instruments			Regulatory and Planning Instruments					
	Taxes	Subsidies and Grants	Quotas or Targets	Mandates on Vehicle Equipment	Mandates on Operator Behavior	Structure of Private Rights	Service Provision	Information Provision	Financing and Contracting
Aging adults and individuals with disabilities (consumers) use Level 5 SAVs		To aging adults and individuals with disabilities to use Level 5 paratransit or shared services To Level 5 paratransit or shared-service providers to expand services to aging adults and individuals with disabilities					Expedited or privileged access to existing services (e.g., managed lanes, signal priority, or parking facilities) for users of Level 5 paratransit or shared services	Public information campaign targeted to aging adults and individuals with disabilities regarding Level 5 paratransit and shared services	

5. Suggestions for In-Depth Evaluations

The objective of this study is to define specific policy and planning actions at the state, regional, or local levels that could be implemented to help societal impacts of CV and AV technologies to be internalized in market decisions made by individuals and organizations. For this study, researchers are interested in the overall categories of policy instruments and planning tools. Realistically, the number of policy and planning strategies (and the specific actions that comprise them) that could be evaluated in an in-depth manner must be narrowed to a discrete set for Task 5: In-Depth Evaluation of Feasibility, Applicability, and Impacts of Policy and Planning Actions.

The results of Task 3 offer a diverse range of strategies for consideration by any number of government agencies and stakeholders. During Task 4, the research panel will review the research performed to date and provide direction and guidance toward prioritized policy and planning strategies for detailed assessments. To facilitate the prioritization process, the team filtered the results of Task 3 to a discrete set of strategies by considering two specific questions:

1. Which policy, regulatory, and planning instruments fall within the general purview of state, regional, and local governments?
2. Which policy, regulatory, and planning instruments have the greatest near-term applicability?

Using these two criteria, the team suggests consideration of the strategies listed in Table 14 for further in-depth assessments. The table highlights the consumer and producer actions across all externalities that could be addressed by the individual policy or planning strategy.

Following the selection of the strategies, the research team will conduct the in-depth assessments as topically oriented white papers, focusing on whether the policy or planning strategy can be executed for the intended purpose. The viability assessments of each strategy will use at a minimum the following 10 criteria:

1. **Effectiveness:** What evidence is available to evaluate the effectiveness of the strategy? What are the gaps in information? What are possible unintended consequences?
2. **Political:** How well will the strategy likely be accepted by decision makers and the general public?
3. **Institutional:** What are the laws and formal provisions that define roles and responsibilities of all the organizations involved in implementing the strategy?
4. **Operational:** If the strategy is developed, will it be used? Operational issues include internal issues, such as labor objections, manager resistance, organizational conflicts, and policies.

5. **Geographic:** At what geographic scale(s) can the strategy be implemented? Are their urban and rural differences?
6. **Financial:** What are the rough estimates of costs to see if they match general expectations or would have an acceptable return on investment?
7. **Applicability:** Which technologies apply? To what levels of AV/CV market penetration would they apply? How does viability shift with market penetration levels?
8. **Impact on market decisions:** To what degree will the strategy make a difference in market decisions made by individuals and organizations?
9. **Level of government:** Is this strategy most appropriate at the local, regional, or state level?
10. **Ownership model:** Is the strategy most effectively applied in a private ownership model or a subscription model?

Based on the findings of the evaluation, overall judgments will be made about the relative effectiveness of the evaluated policy and planning strategies.

Table 14. Suggested Policy and Planning Strategies for In-Depth Assessments.

Instrument	Category	Policy/Planning Strategy	Consumer or Producer Externality Actions Potentially Addressed by Strategy
Economic	Taxes	Apply road pricing, including tolling, parking pricing, and emerging applications of distance-based pricing to reduce travel demand	• Consumers of AVs do not significantly increase overall travel demand • Consumers do not drive farther for housing, even though the technology decreases travel cost • Consumers use Level 5 vehicles to avoid parking in urban centers • Consumers use SAVs rather than privately owned AVs, which minimizes VMT growth
Economic	Subsidies	Accelerate CV market penetration by subsidizing equipped vehicles, both original equipment and after-market retrofit of conventional vehicles	• Producers develop and sell safe CVs • Consumers purchase vehicles with V2V/V2I capabilities • Consumers purchase and use aftermarket V2V safety applications • Producers develop and sell interoperable V2V or V2I mobility and environmental applications • Consumers use V2V/V2I mobility and environmental applications
Economic	Subsidies	Subsidize shared-vehicle services to minimize VMT growth and support transit services, including paratransit	• Private shared-vehicle services operate SAVs • Private shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit • Consumers use SAVs rather than privately owned vehicles
Economic	Subsidies	Create incentives such as pre-tax transit benefits and location-efficient mortgages to support market penetration of SAVs near transit nodes	• Private shared-vehicle services operate SAVs • Private shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit
Regulatory/ planning	Mandates for operator behavior	Establish, codify, and enforce CV and AV operator requirements, including training, making installation and use of applications a component of driver training and licensing	• Consumers are attentive to V2V and V2I safety warnings in vehicles • Consumers purchase safe AVs • Consumers follow safe AV maintenance and operating procedures • Consumers use SAVs rather than privately owned AVs • Private shared-vehicle services operate SAVs

Table 14. Suggested Policy and Planning Strategies for In-Depth Assessments (Continued).

Instrument	Category	Policy/Planning Strategy	Consumer or Producer Externality Actions Potentially Addressed by Strategy
Regulatory/ planning	Structure of private rights	Restructure liability regimes, such as limited liability for automobile manufacturers, no-fault insurance, or other policy actions to accelerate market penetration	• Producers develop and sell safe AVs • Consumers purchase vehicles with V2V/V2I capabilities • Consumers purchase and use aftermarket V2V safety applications • Consumers are attentive to V2V and V2I safety warnings in vehicles • Consumers purchase safe AVs • Producers of AVs act upon communications with road operators about infrastructure requirements for safe operations
Regulatory/ planning	Structure of private rights	Implement land use regulations and parking requirements to increase density in support of market penetration of SAVs at transit nodes	• Private shared-vehicle services operate SAVs • Private shared-vehicle services prioritize ridesharing and linkages with line-haul mass transit • Developers build fewer parking facilities or build parking facilities that can be adapted to other purposes
Regulatory/ planning	Structure of private rights	Enact legislation to stimulate CV or AV testing	• Producers develop and sell safe AVs • Producers of AVs act upon communications with road operators about infrastructure requirements for safe operations • Producers develop and sell interoperable V2V or V2I mobility applications • Producers develop and sell connected AVs that harmonize traffic flow • Private shared-vehicle services operate SAVs • Private shared services prioritize ridesharing and linkages with line-haul transit
Regulatory/ planning	Service provision	Invest in CV infrastructure in collaboration with private sector	• Consumers purchase vehicles with V2V/V2I capabilities • Consumers purchase and use aftermarket V2V safety applications • Producers develop and sell connected AVs that harmonize traffic flow • Consumers use V2V/V2I mobility applications • Consumers purchase connected AVs that harmonize traffic flow

Table 14. Suggested Policy and Planning Strategies for In-Depth Assessments (Continued).

Instrument	Category	Policy/Planning Strategy	Consumer or Producer Externality Actions Potentially Addressed by Strategy
Regulatory/ planning	Service provision	Grant AV- and CV-equipped vehicles, including transit and commercial vehicles, privileged access or services (high-occupancy vehicle lanes, signal priority, and parking access)	• Consumers purchase vehicles with V2V/V2I capabilities • Consumers purchase and use aftermarket V2V safety applications • Producers develop and sell safe AVs • Consumers purchase safe AVs • Producers of AVs act upon communications with road operators about infrastructure requirements for safe operations • Private shared services prioritize ridesharing and linkages with line-haul transit • Consumers use V2V/V2I mobility applications • Consumers purchase connected AVs that harmonize traffic flow • Consumers purchase AVs that are lower polluting or have eco-driving operating objectives
Regulatory/ planning	Information	Increase public awareness through education, training, communication, and outreach to stimulate consumer action and supportive public investment	• Consumers purchase vehicles with V2V/V2I capabilities • Consumers purchase and use aftermarket V2V safety applications • Consumers are attentive to V2V and V2I safety warnings in vehicles • Consumers purchase safe AVs • Private shared services prioritize ridesharing and linkages with line-haul transit • Consumers use V2V/V2I mobility applications • Consumers are attentive to V2V and V2I safety, environmental, and mobility messages in vehicles • Consumers purchase connected AVs that harmonize traffic flow • Consumers use SAVs rather than privately owned AVs • Consumers purchase AVs that are lower polluting or have eco-driving operating objectives • Consumers use SAVs rather than privately owned AVs • Aging adults and individuals with disabilities purchase Level 5 AVs or use Level 5 SAVs

Table 14. Suggested Policy and Planning Strategies for In-Depth Assessments (Continued).

Instrument	Category	Policy/Planning Strategy	Consumer or Producer Externality Actions Potentially Addressed by Strategy
Regulatory/ planning	Financing/ contracting	Implement new contractual mechanisms with private service providers, including shared data arrangements	• Producers of AVs act upon communications with road operators about infrastructure requirements for safe operations • Producers develop and sell interoperable V2V or V2I mobility applications • Producers develop and sell connected AVs that harmonize traffic flow • Private shared-vehicle services operate SAV • Consumers purchase connected AVs that harmonize traffic flow • Consumers purchase Level 5 AVs or use Level 5 SAVs

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Appendix A: Traffic Crashes Briefing Paper

What Is the Crash Externality?

Crash externalities occur because when someone drives a vehicle, they not only increase their own risk of a crash, but also increase crash risks for other motorists, as well as pedestrians and bicyclists. These externalities or social costs of driving are conceptually different from the private costs imposed on individuals, which may be significant. Individuals can die, suffer injuries, or incur damage costs. As a response to such costs, a motorist can refrain from driving, exercise greater care while driving or insure themselves (and vehicles) against possible damages that occur as a consequence of driving. The motorist then internalizes such costs (Jansson, 1994). Some traffic crash costs however are not internalized by the motorist. A pedestrian struck by a vehicle is an instance of an external cost, as are the consequences of two vehicles colliding. In such cases, the total costs of the crash are not borne by the individual (Edlin and Karaca-Mandic, 2006; Parry, et al, 2007; Anderson et al, 2014). There are the costs inflicted on fellow road users and spillover effects on the rest of society (e.g., net output losses, ambulance support, and hospital treatment). Values are also sometimes also put on intangibles such as physical pain or loss of quality of life.

The National Highway Traffic Safety Administration (NHTSA) estimated the total economic cost of motor vehicle crashes in the U.S. in 2010 as $242 billion (NHTSA, 2015a). The cost components included productivity losses, property damage, medical costs, rehabilitation costs, congestion costs (including travel delay, excess fuel consumption, and increased environmental impacts), legal and court costs, emergency services such as medical, police, and fire services, insurance administration costs, and costs to employers. Such costs for 2010 were equivalent to $784 for every U.S. resident and 1.6 percent of the U.S. Gross Domestic Product (GDP). Thus, crashes pose a huge public health and economic cost to society. When intangibles are factored in (i.e., pain and reduced quality of life), the total societal harm from motor vehicle crashes in 2010 was $836 billion.

All levels of society – the individual crash victims and their families, their employers and society at large – are affected by motor vehicle crashes in many ways. For example, the cost of medical care after a crash is certainly borne by the individual in the form of payments for insurance, deductibles, or uncovered costs and uninsured expenses. It is also borne by society through higher insurance premiums and the diversion of medical resources from other needs such as medical research or basic public health needs (NHTSA, 2015a).

How Significant Is the Crash Externality?

In 2014, there were 32,675 people killed in motor vehicle crashes in the U.S., and an additional 2.3 million injured (NHTSA, 2015b). These estimates represent slight but continuing (with some fluctuation) declines in fatalities and injuries due to traffic crashes. Fatalities have decreased 25% from 2005 to 2014, while injuries have decreased 13%. The economic recession has contributed somewhat to the decline. Fatalities usually decline during periods of economic uncertainty (NHTSA, 2015a). But more importantly, the decline has been attributed to a combination of influencers including infrastructure, technology, and behavior changes. For example, in terms behavior change, NHTSA estimates that in 2010 seat belt use *prevented* 12,500 fatalities and 308,000 serious injuries. In terms of technology, since 2000, there have been a number of significant safety improvements in the on-road vehicle fleet. NHTSA identifies these as advanced air bags, better side impact protection, tire pressure monitoring systems, interior padding, improved seat belts, improved vehicle conspicuity, anti-lock brake systems, and electronic stability control. But the fact that there were more than 32,000 fatalities in 2014 shows that considerable safety improvements are still necessary.

Unlike light vehicle casualty rates, motorcycle fatalities and injuries have generally increased over the past decade (NHTSA, 2015a). Per vehicle mile traveled in 2010, a motorcyclist was about 30 times more likely than a passenger car occupant to die in a crash and five times more likely to be injured. The lack of external protection provided by vehicle structure, lack of internal protection provided by seat belts and air bags, their speed capabilities, the propensity of riders to be ejected and become airborne, and their relative 2-wheel instability contribute to make motorcycles the most hazardous form of vehicle. NHTSA estimated that in 2010 motorcycle crashes cost nearly $13 billion in economic impacts and $66 billion in societal harm as measured by comprehensive costs. Compared to other motor vehicles, these costs are disproportionately caused by fatalities and serious injuries and happen with much fewer VMT.

Of course, crash risks are not limited to occupants or operators of motorized vehicles. Of the more than 2 million roadway injuries in 2011, 69,000 were pedestrians and 48,000 were cyclists (Anderson, 2014).

What Factors Contribute to the Crash Externality?

Drivers, vehicles, and environmental conditions can all cause crashes. However, human errors are a critical cause of more than 90% of crashes at the national level (NHTSA, 2015c).[1] The attribution of critical reasons by NHTSA was as follows:

- Drivers, 2,046,000 crashes (94%)
- Vehicles, 44,000 crashes (2%)
- Environment, 52,000 crashes (2%)
- Unknown, 47,000 crashes (2%)

The driver-related critical reasons are broadly classified into recognition (41%), decision (33%), performance (11%), and non-performance (7%) errors. Recognition errors include those related to driver's inattention, internal and external distractions, and inadequate surveillance. Such errors would include the broad category of distracted driving, for which the economic cost of crashes almost $40 billion in 2010 (NHTSA, 2015a). Decision errors include driving too fast for

[1] The "critical reason" is defined as the immediate reason for the pre-crash event as collected in NHTSA's National Motor Vehicle Crash Causation Survey, conducted from 2005 to 2007.

conditions or too fast for curves, and making false assumptions of others' actions or illegal maneuvers. The economic cost of speed-related crashes, alone, was $52 billion in 2010. Alcohol involved crashes involve both impaired judgment (decision errors) and perception problems (recognition errors). NHTSA estimated that crashes in which alcohol was the cause resulted in $43 billion in economic costs. The first two types of driver-related errors (e.g., recognition and decision) represent $135 billion in economic costs. In about 11% of the crashes, the critical reason was performance error such as overcompensation, poor directional control, etc. Sleep was the most common critical reason among non-performance errors that accounted for 7% of the crashes. If AV and CV technology mitigate these any of these types of errors, there would be a substantial benefit to society.

In the National Motor Vehicle Crash Causation Survey, vehicle-related factors were inferred through external, easily visible factors and were identified primarily as problems with tires, brakes, steering column, etc. Environment-related causes were defined as roadway or atmospheric conditions. Nearly 50% of the environment-related crashes were attributed to slick roads (e.g., ice, loose debris, etc.), and glare was a critical reason in another 17% of environment-related crashes. Weather conditions, including fog, rain, snow, or other conditions were a factor in 8% of the environment related causes.

How Could CVs and AVs Lead to Desirable Outcomes?

Safety is the primary benefit of V2I and V2V applications. Safety warnings provided by V2V and V2I technology enable drivers to take actions that could reduce the severity of collisions or avoid them. Warning systems simply warn the driver when a collision is likely, but do not automatically apply the brakes. There are many potential V2I and V2V safety applications as ITS-JPO notes on its website (http://www.its.dot.gov/connected_vehicle/connected_vehicle_apps.htm); however, to date only small research deployments have occurred to evaluate the effectiveness (GAO, 2015). Much of the existing evidence is from U.S. DOT analysis of existing data, without consideration of the effectiveness of specific applications on public roadways.

In 2010, NHTSA estimated the annual frequency of three different types of target crashes (i.e., light-vehicle, heavy-vehicle, and all-vehicle) that might be addressed with V2V and V2I safety applications (Najm, 2010). The analysis excluded drivers with physiological impairment such as intoxication or drowsiness because such driver conditions were believed to be addressed by AVs. This research found that fully mature:

- V2I systems potentially address about 26% of all-vehicle target crashes, 27% of all light-vehicle target crashes, and 15% of all heavy-truck target crashes annually
- V2V systems potentially address about 79% of all-vehicle target crashes, 81% of all light-vehicle target crashes, and 71% of all heavy-truck target crashes annually.
- Combined V2V and V2I systems potentially address about 81% of all-vehicle target crashes, 83% of all light-vehicle target crashes, and 72% of heavy-vehicle target crashes.

The study concluded that V2I systems appear to bring small marginal benefits to the safety benefits of V2V systems alone.

In 2012, a study commissioned by FHWA used existing crash data and estimated the number, type, and costs of crashes that could be prevented by 12 different V2I application areas (Eccles, 2012). The application areas included:

- running red light/stop sign
- driver-gap assist at signalized and stop-controlled intersections
- curve speed warning
- work zone warning for reduced speed
- spot treatment weather conditions
- speed zone warning
- work zone alerts
- infrastructure pedestrian detections
- at-grade rail crossing
- lane departure warning.

This study projected that the 12 V2I application areas would prevent 59% of single vehicle crashes and 29% of multi-vehicle crashes. The study found that the lane departure application area represented the greatest potential to improve safety. The study cautions that the actual number of crashes addressed depends on the effectiveness of the application and the extent to which it is deployed.

Similarly, the GAO (2015) pointed out that organizations researching the benefits of V2I have noted that the benefits depend on a variety of factors, including the size and location of the deployment, the number of roadside units deployed, the types of applications that are deployed and that some applications require a majority of vehicles to be equipped before reaching optimum safety benefits. More extensive evaluative data on the benefits of specific V2I applications is expected from the Connected Vehicle Pilot Deployment program sites (New York City, Tampa, and Wyoming) that are just starting up.

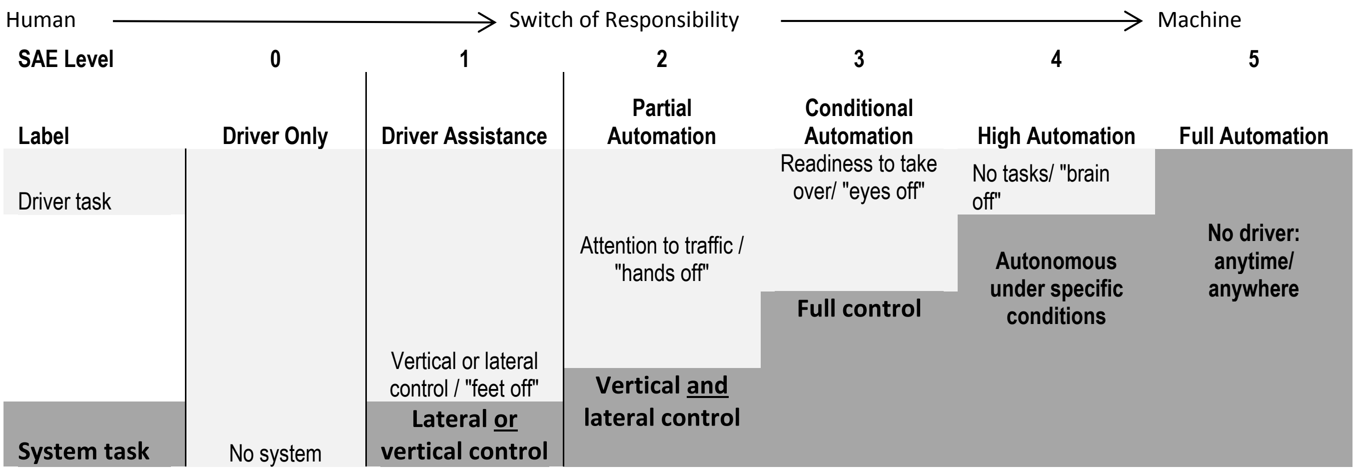
NHTSA's 2014 report on the readiness of V2V technologies assessed the technical strengths and weaknesses of V2V devices installed in light vehicles as part of the Connected Vehicle Safety Pilot Model Deployment. The study found that the V2V devices were able to transmit and receive messages and that safety applications enabled by V2V proved effective in mitigating potential crashes (Harding, 2014). Applications included:

- forward collision warning
- electronic emergency brake light
- do not pass warning
- intersection movement assist

- blind spot warning + lane change assist.

But various aspects of the technology still need further investigation including: the impact of spectrum sharing, ability to mitigate V2V communication congestion, incorporation of GPS positioning advancements to improve V2V relative positioning, remedies to address false positive warnings from the safety applications, and driver-vehicle interface performance.

While safety is a primary motivation for AV development, other motivations that have been expressed by automakers include convenience, mobility and environmental benefits. AV technologies represent a switch in responsibility for the driving task from human to machine to accommodate these benefits (see Figure A-1).



Source: Highly automated driving, Dr. Rene Grosspietsch, 04.09.2015

Figure A-1. Switch of Responsibility in Driving Task with AVs.

As more of the driving task is switched to the automated driving system as with SAE Levels 3-5, AVs should mitigate a significant portion of the accident risk stemming from human error. But since vehicles at SAE levels 3-5 are not yet on the market, evidence on performance vis-à-vis a human driver is sparse. One recent study compared automated vehicle crash rate to data from the SHRP2 naturalistic driving study (Blanco, 2016). The research found that self-driving cars in autonomous mode had significantly fewer crashes; results were caveated by pointing out the uncertainty of this conclusion given the low exposure for self-driving vehicles (about 1.3 million miles in the study) compared to the SHRP 2 NDS (over 34 million miles).

Given evidence to date, on the safety benefits of AVs and CVs, this research analyzed the potential impact of AVs and CVs on the factors that cause crashes.

Crashes due to Driver-Related Errors

AV and CV technologies should mitigate a large number of driver-related errors and substantially benefit society.

- **Recognition Errors**. Crash risks can be reduced if warnings are received in a timely manner and heeded by drivers. For AVs, the impacts on recognition errors vary by level of automation. For level 3, the automated driving system monitors the driving environment and is in control of the driving task. It may request intervention from the human driver at any time, particularly in dangerous situations (unusual traffic patterns or inclement weather). Much research suggests that this task switching is difficult to do and may introduce new types of crashes if switching is difficult (Jannsen and Kenemans, 2015). At levels 4 and 5, the automated driving system assumes all aspects of the driving task and does not expect a human driver to intervene. We can expect these vehicles to reduce crashes caused by human recognition errors. However, AVs may have difficulty identifying unusual objects that are easy for humans to identify, e.g. distinguishing a cardboard box (which can be driven over) from a concrete block (which cannot). Thus, they could cause different types of recognition-based errors and crashes.

- **Decision Errors.** V2I technology would be expected to provide safety alerts that would warn drivers of roadway hazards; thereby increasing safety. However, if the RSE fails (such as the traffic signals that V2I technology relies on communicating with) the cars may not be able to interpret the signals of a traffic officer directing traffic. V2V safety applications, such as do not pass warnings and intersection movement assist, would warn drivers of the danger of an impending unsafe maneuver, reducing accident risk. AVs in control of the driving environment (levels 4-5) would obey traffic laws reducing decision errors. At level 3, the driver would remain in control of the driving task and thus, be in a position to make decision errors.
- **Performance Errors.** CV technologies would have no effect on performance errors. Prior discussion points out the significant issue of performance gaps at level 3 automation. When the driver is taken out of the loop completely in level 4+, performance errors should decrease. However, with higher levels of automation there is the possibility of over-reliance on the automated driving system and driving skill degradation, which could result in more serious consequences in the event of a system failure.
- **Non-Performance Errors**. Sleep was the most common critical reason among non-performance errors. V2I and V2V safety warnings should be able to assist drowsy drivers to operate their vehicle more safely; however the alerts might prove ineffective for drivers who have fallen asleep. A sleeping driver might experience a performance gap in taking over the wheel of a level 3 AV. At higher levels of automation, a driver should expect to be able to sleep. So the highest probability of enhanced safety is with AV levels 4 and 5.

Crashes Due To Vehicle Errors

While mechanical errors may decrease, new types of electronic errors could be introduced. For safety benefits to be enhanced, AV and CV systems would need to have heightened requirements for maintenance and upkeep of the hardware and software systems. What if the sensors do not work? How can a driver know if a CV safety message has not been sent and received appropriately?

The technologies may introduce new cybersecurity vulnerabilities. The technology implied by CVs and AVs could be of very high interest to hackers. All entry points into the vehicle, such as Wi-FI, the OBD-II port, and other points of potential access to vehicle electronics, could be potentially vulnerable to real-time intrusion (hacking) that could affect the mechanical operation of the vehicle. Since a very small percentage of accidents are caused by mechanical errors, this should have little actual negative consequences in terms of the safety benefits of CV or AV technologies. But as highlighted by the 1.2 billion Toyota settlement after a four-year criminal probe into its handling of a spate of sudden accelerations in its vehicles highlighted, one major high-profile mechanical failure of an AV could have profound implications for deployment of the technology and the realization of benefits.

Crashes Due To Environment Errors

V2I safety applications would enable vehicles to have 360-degree awareness to inform a vehicle operator of environment-related hazards such as a slippery patch of roadway, a sharp ramp curve, and to reduce crashes through advisories and warnings. V2I safety applications would inform drivers approaching an area with adverse weather conditions of the need to reduce speed or divert to safely navigate through or avoid the adverse weather impact area. Thus fully mature V2I technologies definitely have the capability to reduce crashes due to environmental errors.

The safe operation of AVs in adverse weather conditions is uncertain (Boston Consulting Group, 2015). Environmental conditions (e.g., rain or snow) might have a detrimental effect on the safe performance of AVs. Snow might cover lane markings so these are not readable by LIDAR and cameras mounted on vehicles. Heavy rain might do damage to the LIDAR mounted on a car's roof, causing technology failure. The question is: whether AVs are safer "drivers" than human drivers under such conditions.

Table A-1 summarizes how CVs and AVs affect the factors that cause traffic crashes.

Table A-1. How CVs and AVs Might Mitigate Causes of Traffic Crashes.

What are the primary factors?	What are the secondary factors?	How might CVs and AVs affect these factors?
Driver-related errors	Recognition errors	If available and heeded, CV safety messages could mitigate recognition errors. AVs at high and full levels of automation (SAE 4-5) would be in full control of the driving tasks – eliminating inattention or distraction errors assuming that the hardware and software is functioning appropriately. At lower levels, in which control is shared between the vehicle and the driver, the driver might not be able to take over the driving task safely.
	Decision errors	If available and heeded, CV safety messages could provide prompts to drivers to safely navigate hazardous driving situations. Drivers may still disobey the traffic laws. Leve 4 AVs would obey traffic laws, reducing decision errors. At lower levels of automation (level 3), the driver would remain in control of the driving task and thus, in a position to make decision errors.
	Performance errors	CV safety messages would have no effect on performance errors. While successful at ameliorating performance errors, AV level 3 could introduce new types of performance gaps.
	Non-	CV safety messages would reduce errors made by drowsy drivers;

What are the primary factors?	What are the secondary factors?	How might CVs and AVs affect these factors?
	performance errors	however, they may have little effect on sleeping drivers. At AV level 3, drivers might still experience performance gaps due to being drowsy or asleep. At levels, 4 and 5, drivers should expect to sleep.
Vehicle-related errors	Mechanical errors	Mechanical errors decrease but new types of electronic (hardware/ software errors) could be introduced.
	Cybersecurity (vehicle hacking)	As cars become more connected and automated, cybersecurity risks escalate. This is a new factor that shapes the crash externality – it has not been a concern for traditional vehicles.
Environmental Factors	Weather conditions	CV safety applications would inform drivers of adverse road or weather conditions. The safe operation of AVs on the other hand could be negatively affected by adverse weather; on the other hand, AVs could be better at driving over the ice or snow than human drivers.
	Road design features	CV safety messages will provide safety benefits such as work zone, curve speed, left turn assist, do not pass warnings. Such alerts and notifications have the potential to decrease crash risk. AVs might be better or worse at recognizing road features.

Given the significant potential for reduction in driver-related errors, AVs and CVs should bring a positive societal benefit. That said, research has identified three categories of challenges in terms of fulfilling the societal safety benefits of AVs: Driver performance gaps, potential new types of vehicle errors, and operating condition constraints.

Driver Performance Gaps

Safety analysis must consider driver performance gaps. SAE Level 3 vehicles represent a balancing act that attempts to provide drivers with the benefits of autonomy—like not having to pay attention—while ensuring they are ready to take over when needed. There are situations in which safety may not be enhanced. If a driver was texting or reading at the time of the request to intervene, he/she may longer than is safe to take over the driving task.

Studies of automated driving reviewed in Trimble et al (2014) found conflicting safety results for level 3 vehicles. U.S. Army research found that automated vehicles at levels 2 and 3 can improve driving performance through a decrease in total driver workload (e.g., allowing the operator to rest or perform other tasks); whereas the results of a driving simulator study of level 3 vehicles suggested that the conditional automation may hinder driving performance because drivers may be vulnerable to persisting fatigue and associated reduction in situational awareness when normal vehicle control is re-engaged. The study recommends that solutions that will maintain driver engagement and address the vulnerabilities of fatigue-prone drivers should be sought. On the other hand, studies of special applications of highly autonomous vehicles (i.e., driver-less vehicles patrolling borders or used in mining operations) have been successfully and safely operated. These are best considered level 4 automation as even though they can operate without a driver their automated operation is not intended to cover the full range of conditions that would be experienced on public roads.

Trimble et al (2014) also analyzed public statements from various automakers regarding their companies' individual motivations for pursuing automated vehicle production. Safety is a key motivation – along with mobility, productivity, and driver convenience benefits. Many automakers are focused on level 3 automation solutions, following an incremental, level-by-level approach so humans cede control over time.

- BMW Group expects to have vehicles with conditional automation (level 3) functions to be ready for implementation in the 2020 timeframe. BMW described a level 4 prototype, Emergency Automated Operation that does not require driver involvement. If biosensors detect a medical emergency in the vehicle (such as a heart attack), the ESA is able bring the vehicle safety to a stop on the road shoulder and automatically send out an emergency call.
- GM as well has stated that the driver should not be fully removed from the equation (e.g., engaged and aware of the situation and ultimately responsible for the vehicle's operation). GM expects it will be possible to let people disengage from the driving task (level 4) but sees this as much longer term.
- Nissan envisions the car and driver working as a team, akin to the partnership of equestrians and their horses.
- Toyota and Lexus are focusing on technologies that support the driver to be a safer driver; the driver needs to remain fully engaged in the driving process.

Others targeting automation levels beyond Level 3 because it presents the challenge of how to safety transfer control from automated driving system back to the driver, particularly in an emergency.

- Ford wants to go right to level 4, high automation. It expects to have a fully autonomous car within five years that could be deployed in areas where it can supply extremely detailed maps such as freeway driving.
- Volvo's vision is to develop an automation system that does not require human supervision (level 4), and has stated it will accept full liability for its cars while in autonomous mode.
- Google is developing fully autonomous vehicles that do not have a steering wheel for safety, energy, congestion, and car-sharing benefits. It is currently testing level 3 vehicles on roads in California and Texas and expects to test level 5 vehicles soon.

At high and full automation (Levels 4, 5), the automated driving system is solely expected to be in control of the driving task and safety benefits could be achieved in many situations if the AV were a "safer" driver than a human driver in that situation. However, with higher levels of automation, there is the possibility of over-reliance on the automated driving system and driving skill degradation, which could result in more serious consequences in the event of a system failure.

New Types of Vehicle Errors

As more of the driving task is switched to the automated driving system as with Levels 3-5; many technologies (i.e., sensors, motion control, trajectory planning, driving strategy, situational awareness, etc.) need to operate effectively so that the vehicle performs at least as well as a human driver (Trimble et al, 2014).

In 2014 the Casualty Actuarial Society's Automated Vehicles Task Force re-evaluated the National Motor Vehicle Crash Causation Survey study results (noted previously) in the context of an automated vehicle world (Stienstra, 2014). This re-evaluation found that about half of all accidents could be addressed by AVs. The study concluded that driverless cars may be safer than human drivers, but flawed hardware or software could cause accidents, and liability could then fall on manufacturers or installers, in which case, the insurance pricing would fall to product liability actuaries for coverage.

A recent example was some drivers experiences with Tesla's autopilot technology. The autopilot software update enables a vehicle to maintain its speed, keep a safe distance from the vehicle in front, and change lanes automatically. But for some driver's with "hands off" the wheel, the vehicle sometimes veered out of its lane. New types of vehicle errors could be introduced because hardware or software could be prematurely released as in the Tesla example, or inadequately maintained by owners or manufacturers with both factors resulting in decreased safety benefit.

Cybersecurity issues are another potential source of error. Computing and digital systems have a tendency to become more fragile and susceptible to faults and failures because of cyber-attacks and software and hardware defects, as well as accidental defects introduced by developers. Cybersecurity—in the context of vehicle systems, refers to security protections for systems in the vehicle that actively communicate with other systems or other vehicles (Garcia, et al, 2015). While cybersecurity issues are a challenge for CVs, security becomes a bigger concern with L4 and L5 vehicles, in which software and connectivity plays a much bigger and more critical role for the safe driving of vehicles. In case of cyber-attack the safety of passengers in an AV and other road users could be at risk. In case of hacking and stopping fleet of AVs, the transportation system could be halted with potential safety reduction (even though no real case of malicious car hacking has been reported yet). Unlike traditional vehicles, AVs may be vulnerable to cyberattacks that can spread from vehicle to vehicle, which may constitute a new type of safety threat. Cybersecurity, therefore, would be a new factor that shapes the existing crash externality. Autonomous vehicle systems should be developed to bear such dangers in mind and must be equipped with defensive capabilities and measures such that they can be able to respond.

Another new type of vehicle related error relates to an automation system's ability to avoid driving conflict situations (Sivak and Schoettle, 2015). An experienced driver exercises the accumulated wisdom of predictive knowledge. Can automation match that predictive knowledge? The automated driving system is learning from driving it experiences as an iterative process. So the vehicle is basically learning from itself. The automation system may not know how to behave in unknown situations, and in some cases the response may lead to a crash. For example, the system may fail to respond to a hazard. Conversely, it may respond inappropriately to a non-hazard (e.g., braking hard for a piece of paper in the road).

Constrained Operating Conditions

Safety benefits are enhanced through widespread use of AVs and concomitant reduction of human errors. But a factor limiting the safety benefits of AVs is that automated vehicle applications may only operate under specific conditions, and these conditions can be constrained by vehicle location, speed, and/or dynamics (Smith et al, 2015). Based on these constraints, AV applications may only address certain pre-crash scenarios. Pre-crash scenarios depict specific vehicle movements and dynamics as well as the critical event occurring immediately prior to the crash. For instance, Smith identifies GM's Cadillac CTS Super Cruise application – Level 3 automation for motorway environment -- as working well in both bumper-to bumper traffic and on long road trips in light traffic but cautions that more-complicated driving conditions may be challenging. Staying centered in a lane on a highway is much less demanding than staying centered on a road in a crowded city where lane markings can be less visible, other vehicles may block a camera's view of them, and bicyclists and pedestrians travel alongside cars and trucks.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External?

The preceding discussion provides an overall discussion of the traffic crashes externality, along with the roles of AV and CV in mitigating the externality. Given these issues, the scale of safety benefits depends on different actors taking specific actions. We identified seven distinct actions that producers and potential consumers of vehicles equipped with AV and CV technologies can take to realize beneficial outcomes:

1. Producers develop and sell safe AVs[2]
2. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure safe operations (across different use cases/operating conditions)
3. Consumers purchase vehicles with V2V /V2I capabilities
4. Consumers purchase and use aftermarket V2V safety applications
5. Consumers are attentive to V2V and V2I safety warnings in vehicles
6. Consumers purchase safe AVs
7. Consumers follow safe AV maintenance and operating procedures.

[2] This action is encompassing of Levels 3-5, so it would pertain to such specifics as producers developing and selling Level 3 AVs with the proper human-machine interface; thus, reducing driver performance gaps.

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Appendix B: Congestion Briefing Paper

What Is the Congestion Externality?

While it may not appear so at first glance, congestion is fundamentally an economic phenomenon (FHWA 2008). This phenomenon is related to one of the most basic ideas in economics: the (im)balance of supply and demand. We live in a world of mostly finite resources, and an economy usually helps society efficiently allocate resources under scarcity. People who want a good (or "demand" it) must pay people who are willing to supply the good. Once the parties reach an agreed upon price, the good is exchanged.

A successful economic transaction is limited by the available supply, however. Under traditional market economics, if the demand for a good exceeds its supply – all things held equal – the price will increase. Unfortunately, not all goods are able to fluctuate their price in response to changes in demand. When a good cannot adjust its price and demand for the good exceeds available supply, a situation known as a shortage occurs, and some of the consumers who wish to purchase the good will not receive it.

Special circumstances can exist, however, where a good is *non-excludable* (difficult to keep people from using it) and *non-rivalrous* (once the good is supplied, it costs little or nothing to provide to other consumers). Under this situation – what economists call a public good – individuals may demand the good beyond what can reasonably be supplied. When this happens, a condition called a market failure occurs, wherein all consumers are made worse off as a result of the imbalance between supply and demand.

Non-tolled roads are a classic example of a public good leading to a market failure. When too many motorists take to the road, congestion sets in and traffic moves less efficiently than it would otherwise: people lose time, fuel is wasted, and pollution worsens. Each additional driver that takes to the road adds to the congestion that all drivers bear, although each motorist does not bear the full costs of their decision to drive. Motorists pay the costs that they incur directly, like the fuel they use and their personal travel time, but do not bear the costs that they impose on other drivers. The other costs imposed on society are known as the external costs (or the externality) from congestion: the additional delay, environmental harms, and wasted fuel are all transferred to society.

How Significant Is the Congestion Externality?

The costs from congestion are real and quite large. In fact, according to the *2015 Urban Mobility Scorecard*, "travel delays due to traffic congestion caused drivers to waste more than 3 billion gallons of fuel and kept travelers stuck in their cars for nearly 7 billion extra hours – 42 hours per rush-hour commuter" (Schrank, et al. 2015). The total cost to the United States is a hefty toll: $960 per commuter, or $160 billion for the nation as a whole.

What Factors Contribute to the Congestion Externality?

Congestion can be recurring and non-recurring. Recurring congestion is caused by shortages of supply and excesses of demand, and inefficiencies in operating or managing the transportation system. Non-recurring factors include incidents like vehicle crashes, construction, weather, and other temporary disturbances (Paniati, 2003).

How Could CVs and AVs Lead to Desirable Outcomes?

AVs and CVs are likely to affect both the recurring and non-recurring factors that contribute to congestion – potentially in both positive and negative ways – resulting in an uncertain and likely mixed net overall effect.

Effect on Recurring Congestion

Insufficient Supply

AV/CVs could potentially drive with greater precision and control than humans (Smith 2012). This ability could plausibly enable infrastructure operators to redesign aspects of their facilities to accommodate more traffic in a variety of ways. For example, by reducing lane size and shoulder width, an agency could restripe a road and add a lane. This would effectively increase the supply of roads. It is worth noting, if this were to occur, it would likely be over the long term, as it would require all (or nearly all) vehicles be capable of driving with a high level of control. Since the vehicle fleet turns over slowly, even in optimistic projections, this would likely remain a distant proposition. Additionally, new lanes may only be possible in areas with sufficient spacing, so already lane-dense roads may benefit less than locales with existing excess space. Rural, and less-dense areas in general, would likely benefit more than dense urban areas.

Finally, SAVs may offer benefits for congestion as well. Provision of SAVs could reduce VMT of users and lead to higher density development, potentially resulting in further lower per-trip VMT. SAVs could be used to provide first-mile / last-mile linkages to mass transit systems, or to facilitate ridesharing by pooling occupants, thus reducing congestion.

Excessive Demand

In terms of demand, AVs and CVs could decrease the cost of driving, thus inducing additional VMT (Anderson et. al, 2014). Automated and connected vehicles are likely to reduce the costs[3] associated with driving, namely the opportunity cost of a motorist's time, fuel costs, and a reduction in the costs associated with fewer crashes. When the cost for an activity decreases, all things equal, demand for that activity will increase.

In this case, it is unclear how much or how quickly the cost of driving will decrease, or how much a change in price would change the demand for driving. When the costs associated with

[3] These include both direct and indirect costs

driving changed in recent years, motorists have been relatively unresponsive in the short term – indicating that it may require large changes in prices (or a long time horizon) to alter consumer driving behavior. The US Energy Information Administration (EIA) found, for example, that large changes in gasoline prices created minimal change in VMT (Morris 2014). The EIA estimates that the short term price elasticity of motor gasoline (the amount demand changes when price changes) "is -0.02 to -0.04 in the short term, meaning it takes a 25% to 50% decrease in the price of gasoline to raise automobile travel 1%."[4] This evidence indicates that short term changes in the cost of driving will likely have minimal effect on VMT, but it is less clear how changes from AVs and CVs over the longer term will affect VMT.

SAE Level 5 AVs and CVs could also alter demand by enabling individuals who were previously unable to drive to do so (Smith 2012). Persons under the legal driving age, and those who are unable to drive due to disabilities are two potential sources of increased demand to drive. If these populations were legally and otherwise empowered to independently operate a motor vehicle, they could dramatically increase VMT. It is unclear exactly how many people in these groups would choose to take advantage of increased mobility services or options, or how much they would drive given the opportunity – but this could represent a large share of the US population.

As an example, the US Census Bureau estimates that 1 in 5 people in the US have a disability, and more than half of those are severely disabled (US Census Bureau 2012). Stated differently, about 56.7 million people are disabled, and more than 23.4 million are severely disabled. These groups are much more likely to be unemployed than the general population, and are likely to have a lower income as well.

Younger populations, if capable of riding unescorted in SAE L5 AV/CVs, could also add significant numbers to VMT. The US Census Bureau estimates that about 26% of the US population (or about 83 million people) is less than 16 years of age (US Census Bureau N.D.). If this population also were capable of riding unescorted in personal vehicles, they could add significantly to VMT as well.

Finally, under fully-automated (SAE level 5) vehicles, the opportunity costs of a motorist's time could be completely removed through the motorist not even being present in the vehicle. This could enable many different services and opportunities for motorists, which would also likely increase demand for vehicular travel. Like the development of the transcontinental railroad, the US highway system, commercial aviation and the internet all created new and unseen opportunities for economic development, so too could a true self-driving vehicle create new demand and markets currently impossible to anticipate or estimate – although it is likely an understatement to say the impact could be very large.

[4] Price elasticities are generally bidirectional.

System Efficiency

System efficiency is a difficult issue to consider due to its complexity. In basic terms, efficiency is defined as the amount of inputs required to create a given output. In this case, we are considering how many people or goods are able to move on a roadway within a given time and space. CVs and AVs could plausibly affect system efficiency in a variety of ways. As mentioned above, they could plausibly drive with greater precision and accuracy than human controlled vehicles, enabling greater overall efficiencies of vehicle flow. Beyond this effect, there are a variety of ways the vehicles could affect efficiency.

The CV system has envisioned a variety of V2V- and V2I-enabled mobility-focused applications that could increase the efficiency of the vehicle system (USDOT, 2015). For example, dynamic speed harmonization (SPD-HARM) and cooperative adaptive cruise control (CACC) are two applications that could increase system efficiency by enabling vehicles to coordinate their actions in certain circumstances. This communication and coordination could enable a traffic management center to optimize traffic flow through “a more proactive approach for predicting queues and congestion" (USDOT, 2015).

Just as with any complex undertaking however, system efficiency depends on the effectiveness of implementation. A variety of barriers could derail or retard effective implementation. As one example, in the federalist system of government, the federal government must rely on state and local governments as partners in governance and implementation. It is unclear if NHTSA has the legal authority to mandate the requisite CV V2I roadside infrastructure (Harding, et al, 2014). If state or local governments choose not to implement this roadside equipment (RSE) without a NHTSA mandate, system efficiency might not increase, or could even plausibly decrease (GAO 2015).

CVs also especially rely on the network effect, or the condition that occurs when the benefit a good provides to a user increases as the number of users increase (a common example of this phenomenon is the value of a telephone). CVs use inter-vehicle communications as the foundation for all benefits, so if uptake is slow or low, the benefits provided will similarly languish. Additionally, if the market penetration and use of mobility applications is low, efficiency will also remain low (Dingus, 2015). The CV system, as currently designed, only provides information to drivers, who must then decide how to act on the information. In such a voluntary system, achieving sufficient adoption and use of mobility-enhancing applications to receive a benefit may be a significant challenge. For example, a recent study found that some drivers did not feel comfortable following the advice given by a CV application in a test environment (Dingus, 2015). If drivers similarly do not follow the advice of mobility (or other) applications, they could fail to provide a benefit, or the benefit could be diminished.

Finally, interoperability and standardization of CV applications is required for many benefits, but it is unclear if automakers must make all of their CV applications interoperable with other OEMs’ applications. As referenced earlier, NHTSA’s legal authority in the motor vehicle space is broad, but not unlimited (Harding, et al, 2014). The Safety Act grants the agency broad powers to set standards and regulate motor vehicles and their associated equipment for safety purposes, however it does not grant the agency such authority over systems related to mobility and environment. Without this mandate, it is unclear if OEMs will develop and implement interoperable environmental or mobility applications (GAO 2015). Without such interoperability, it is unlikely affected applications will reach the critical mass point of users required to receive benefits.

Effect on Non-Recurring Congestion

AVs and CVs are likely to decrease the frequency of crashes, which should result in decreased congestion from non-recurring sources (see the safety section for an in-depth discussion of advanced vehicle technologies effect on crashes). The safety benefits depend on regulators mandating the CV technology, automakers producing these vehicles, and consumers adopting and using these safer vehicle technologies.

Construction

The USDOT currently envisions several CV V2V- and V2I-enabled applications that provide information and warnings to motorists about upcoming construction and work zones, which often rely on the installation and use of RSE or TMCs. The *Reduced Speed Zone Warning* application informs vehicles approaching an area with a reduced speed limit – like a work zone – of the impending speed and roadway configuration changes (CVRIA 2015 a).

Another similar application, *Warnings about Upcoming Work Zones*, provides motorists with information about the work zone they are approaching (CVRIA 2015 b). It informs motorists about "work zone activities that may result in unsafe conditions to the vehicle, such as obstructions in the vehicle's travel lane, lane closures, lane shifts, speed reductions or vehicles entering/exiting the work zone." These application can use both V2V and V2I communications.

It is unclear if these applications will improve congestion directly associated with work zones, although it seems likely they could reduce the occurrence of crashes near work zones – and any associated congestion.

It is unclear how or if automated vehicles will alleviate or contribute to congestion resulting from work zones. Thus far, automated vehicle designers have already given construction zone navigation careful thought. Some image recognition systems are capable of identifying warning signs or cones, understanding that these symbols connote a work zone, and acting on this information to drive more cautiously to navigate a changed road configurations (Amadeo, 2014). It is unclear how these behaviors will change over time, and what impact – if any – automated driving will have on congestion caused by work zones.

Weather

There are also several V2V- and V2I-enabled CV applications envisioned to address driving in inclement weather conditions. The *Spot Weather Impact Warning* application, for example, informs motorists about upcoming dangerous weather that could affect driving conditions (CVRIA 2015 c). The weather warnings could include conditions like high winds, flooding, ice, or fog. The application could also provide speed advisories to vehicles. Similarly, the *Variable Speed Limits for Weather-Responsive Traffic Management* application gathers information from connected vehicles about weather conditions, analyzes these against historical data, and can recommend speed advisories or provide warnings about road conditions in real time (CVRIA 2015 d). These applications and their associated warnings focus on safety and would likely decrease crashes, however it is unclear if they will decrease congestion related to inclement weather.

It is unclear how well automated vehicles will be able to drive in poor weather. According to media reports, some current automated systems are incapable of driving in inclement weather conditions, like during snow storms (Trudell, 2015). Under such conditions, these vehicle systems will often cede control to the human driver. As such, it is unclear how – if at all – automated vehicles will affect congestion related to driving in challenging weather conditions.

The effects of AV and CV technologies on congestion are summarized in Table B-1.

Table B-1. Congestion Factors and AV/CV Affects.

What are the primary factors?	What are the secondary factors?	How might CVs and AVs affect these factors?
Recurring congestion	Insufficient supply	Better-controlled vehicles (AVs or CVs) could create additional capacity in some circumstances by enabling roadway design changes like tighter lane spacing
	Excessive demand	AVs decreasing the costs of driving and disenfranchised travelers gaining access to L4 or L5 AVs could both increase demand
	System efficiency	AVs and CVs could also lead to better-controlled vehicles, and a better-managed system could improve system efficiency. Poor governance, operations and management, or low market penetration and use of mobility-enhancing applications could result in worsened congestion.
Non-recurring congestion	Incidents	Better controlled and managed vehicles are likely to decrease crashes
	Construction	There are CV applications devoted to work zones, however these focus on safety. Some AVs are capable of recognizing and navigating some work zones. It is unclear if either of these systems will affect congestion related to construction.
	Weather	There are CV applications devoted to warning drivers about poor weather conditions, but these focus on safety. AVs are incapable of driving under certain poor weather conditions, and it is unclear how they could affect congestion in these conditions.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External?

The preceding discussion provides an overall discussion of the congestion externality, along with the roles of AV and CV in terms of the externality. We identified sixteen distinct actions that producers and potential consumers of vehicles equipped with AV and CV technologies can take to realize these beneficial outcomes. Several of these derive directly from the actions that producers and consumers can take to improve safety and reduce crashes, which are a major source of delay.

1. Producers develop and sell interoperable V2V or V2I mobility applications
2. Producers develop and sell safe AVs
3. Producers develop and sell connected AVs that harmonize traffic flow

4. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency and safe operations (across different use cases/operating conditions)
5. Private shared-vehicle services operate SAVs
6. Private shared-vehicle services prioritize ridesharing and linkages with line haul mass transit
7. Consumers purchase vehicles with V2V /V2I capabilities
8. Consumers purchase and use aftermarket V2V safety applications
9. Consumers use V2V/V2I mobility applications
10. Consumers are attentive to V2V and V2I safety and mobility messages in vehicles
11. Consumers purchase safe AVs
12. Consumers follow safe AV maintenance and operating procedures
13. Consumers purchase connected AVs that harmonize traffic flow
14. Consumers of AVs do not significantly increase overall travel demand, though technology reduces the non-monetary costs of driving.
15. Consumers of AVs do not drive farther for housing, even though the technology decreases travel cost
16. Consumers use SAVs rather than privately owned AVs which reduces their travel demand or trip generation

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Appendix C: Pollution Briefing Paper

What are the Environmental Externalities?

A well-functioning transportation system is crucial to the nation's economic vitality and dynamism. Every day people and goods move within and between America's cities and towns, for a near limitless variety of individualized purposes. Yet these individual travel activities come with external societal costs, not directly or fully experienced by those who are making such travel-related decisions. One such set of externalities may be categorized as environmental costs, which may be broken into three major categories, including global air pollution, local air pollution, and noise pollution.

While much has been written on environmental externalities, much remains unknown regarding how technological developments will impact them. In particular, recent and pending advances in connected vehicle (CV) and automated vehicle (AV) technologies have the potential to introduce dramatic effects, as will be discussed here. For the purposes of this report, it is assumed that all AVs discussed here are defined as vehicles with either National Highway Traffic Safety Administration (NHTSA) Level 3 (L3) or Level 4 (L4) capabilities (Administration 2015), meaning that such vehicles can either drive themselves without human intervention or active monitoring in some (L3) or all (L4) circumstances. For CVs, dedicated-short-range-communication (DSRC) technology is assumed. This report does not quantify the scale of environmental externalities, yet rather seeks to identify a comprehensive framework for assessing the potential for various actions and AV/CV-related factors to influence environmental externalities.

How Significant is the Environmental Externality?

Global Air Pollution

In 2013, transportation sources accounted for about 27% of total U.S. greenhouse gas emissions (GHGs), making it the second largest contributor of U.S. GHGs. Since 1990, U.S.-based GHG emissions from transportation have increased by about 16%, largely attributable to increased travel demand (EPA). Passenger car and light-duty truck VMT increased 35% from 1990 to 2013, indicating a fleet-wide fuel efficiency improvement around 14%. The VMT increase is attributed to several factors, including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. Between 1990 and 2004, average fuel economy among new vehicles declined as light-duty truck sales increased, though vehicle fuel economy began to improve in 2005, largely due to lower light-duty truck market share and higher fuel economy standards . Carbon dioxide (CO_2) is responsible for 96% of the transportation sector's end-use GHG emissions, followed by hydrofluorocarbons and methane (EPA 2015). Passenger cars and light-duty trucks[5] comprise 39% of GHG emissions within the transportation sector, with medium- and heavy-duty trucks accounting for 22%, and the remainder from other modes, such as commercial aircraft, ships, boats, and trains as well as pipelines and lubricants .

GHGs affect the amount of heat retained by Earth's atmosphere by absorbing solar energy, or preventing the loss of heat to space. This process is commonly known as the "greenhouse effect", resulting in climate change effects impacting multiple ecological domains and economic sectors. Moreover, the rate of emitted GHGs is increasing. Total GHG emission have increased by 80% since 1970 (2012), with estimated resulting increases to global surface temperature by approximately 1.4°F over the past century (NAP 2010). In addition to warming effects, other GHG include ocean acidification, and plant growth / nutrition. The oceans are now 30 percent more acidic than before the industrial revolution, due to higher carbon dioxide levels, with negative marine life, fishing, and water-related industry impacts (Change 2007). Furthermore, high carbon dioxide levels have shown to reduce protein concentrations in potatoes and selected grains by 5-14% (Taub, Miller et al. 2008).

The SC-CO_2 model was developed as an attempt to provide a near-comprehensive estimate of climate change damages, accounting for changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. According to this model, the current social cost of carbon (using 3% discount rate) in 2015 is around $37, with costs rising in future years and lower discount rates (IAWG 2013). Yet the magnitude of such costs remain quite uncertain, with Moore and Diaz estimated net costs around six times higher, estimating a total social cost of carbon per metric ton equal to $220 (Moore and Diaz 2015). Litman and Doherty (VTPI) estimate greenhouse gas emissions at 1.7¢ per mile for an average car and 2.4¢ per mile for light trucks.

Local Air Pollution

Gasoline-powered vehicles emit carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HCs), otherwise referred to as volatile organic compounds [VOCs]). CO reduces the flow of oxygen in the bloodstream and can cause respiratory and serious cardiovascular problems (Parry, Walls et al. 2007). HC and NOx react in the atmosphere, in the presence of heat and sunlight, to produce ozone, the main component of urban smog. Ozone can cause harmful cardiovascular impacts, particularly among children, asthmatics, and exercising adults, with negative impacts to visibility and agricultural productivity. Suspended fine (PM_{10}) and coarse ($PM_{2.5}$) particulates pose the greatest health risks, as such particulate matter can penetrate deep into the lungs. The Environmental Protection Agency (EPA) currently regulates light-duty and heavy-duty vehicle emissions for NOx, non-methane organic gases (NMOG), CO, PM, and formaldehyde (HCHO), citing harmful human health-related consequences from exposure. Other surface transportation-related local air pollutants such as mobile source air toxics

[5] Including sport utility vehicles, pickup trucks, and minivans

(MSATs) can cause cancer and result in other serious ailments . Caiazzo et al. estimated that road transportation is the largest contributors for air pollutant-related fatalities, responsible for around 52,800 $PM_{2.5}$-related deaths and approximately 5,000 ozone-related deaths per year (Caiazzo, Ashok et al. 2013).

Local air pollution effects are felt by those closest to the source, with externality costs varying by *who* is exposed to the air pollution, and the *amount* of air pollution inhaled by an individual. Local pollutants tend to concentrate adjacent to roadways, and air pollution costs per-ton are usually higher along busy roads, in high population density areas, in vehicles and in areas where geographic and climatic conditions trap pollution and produce ozone (VTPI). Litman and Doherty (VTPI) estimate urban peak local air pollution costs at approximately 5¢ per average automobile mile. Urban off-peak costs are estimated at a slightly lower 4¢ per VMT to account for smoother road conditions and less stop-and-go traffic. Rural driving air pollution costs are estimated to be an order of magnitude lower at 0.4¢ per VMT (largely due to fewer exposed people).

Sources of Air Pollution

Chester and Horvath identified a comprehensive listing of lifecycle emissions sources stemming from various transportation modes (Chester and Horvath 2009). These included manufacturing, active (running) operation, cold starting emissions, inactive operation (evaporative), maintenance, road construction, parking, refining and distribution, and other sources. The table below illustrates life-cycle shares across each of these sources for GHG, sulfur dioxide (SO_2), CO, NOx, VOC, PM10, and lead (Pb) for model year 2005 light duty gasoline sedans. While shares differ for other vehicle types and have changed since 2005, this table provides an illustration of how various pollutant emissions are distributed across pollutant sources over a vehicle's lifecycle.

From this work's preliminary literature review, it appears unlikely that emissions will change substantially from vehicle maintenance, or other sources. While it is possible that vehicle maintenance may decrease somewhat if intelligent vehicle systems are equipped with better diagnostics, it is also possible that the added CV and/or AV hardware could add new maintenance costs. Similarly, is envisioned here that no substantial emissions changes will be realized stemming from insurance and fixed costs, or roadway lighting and maintenance. Therefore, this document focuses on emissions changes stemming the remaining sources noted in Table C-1.

Table C-1. Lifecycle Pollutant Emissions Sources for a Gasoline Sedan (Chester and Horvath 2009).

	GHG	SO_2	CO	NOx	VOC	PM_{10}	Pb
Manufacture[6]	9%	22%	3%	7%	7%	8%	47%
Operation (running)	61%	4%	56%	50%	16%	29%	0%
Operation (starting)	0%	0%	37%	10%	18%	0%	0%
Inactive operation	0%	0%	0%	0%	26%	0%	0%
Vehicle maintenance	3%	8%	1%	2%	3%	0%	53%
Road construction	12%	26%	1%	20%	24%	54%	0%
Parking infrastructure	1%	4%	0%	2%	1%	4%	0%
Refining & distribution	11%	22%	1%	6%	4%	4%	0%
Other sources[7]	3%	15%	0%	2%	1%	1%	0%
Total	113 mt	102 kg	3754 kg	319 kg	359 kg	69 kg	3 kg

Noise Pollution

Noise is one of the most common environmental exposures in the United States (Garcia 2001). In 1981, the U.S. Environmental Protection Agency (EPA) estimated that nearly 50% of the U.S. population experienced traffic noise exposure high enough to be harmful to health (Simpson and Bruce 1981). With such dated noise exposure data, the U.S. population may be at even greater risk to noise-related health effects, as modern 24-hr societies increasingly encroach on "quiet" periods (e.g., night) (Hammer, Swinburn et al. 2014). Vehicular traffic comprises around 55% of total urban noise, with major contributors including motorcycles, trucks and buses. (Jamrah, Al-Omari et al. 2006, Martin, Tarrero et al. 2006). At low speeds, most noise comes from vehicle engines and drivetrains, while at higher speeds aerodynamic and tire/road noise dominates (Homberger and Perkins 1992). The level of highway traffic noise primarily depends on traffic volumes, speeds, and the number of trucks in the traffic flow stream. Generally, heavier traffic volumes, higher speeds, and greater numbers of trucks increase traffic noise, with other factors including distance from the roadway, road surface composition, terrain, vegetation, and other obstacles (FHWA 2011, VTPI 2015).

Noise pollution can have adverse impacts on human health (Georgiadou, Kourtidis et al. 2004). Effects can include annoyance, deterioration of sleep quality, hearing loss from long-term exposure, stress-related ischemic heart disease, mental illness, and even death (Mato and

[6] Including tire production

[7] Including emissions stemming from insurance, fixed costs, roadway maintenance, and lighting.

Mufuruki 1999) (Nelson 1987) (Morrell, Taylor et al. 1997). Litman and Doherty estimated traffic noise costs in urban and rural areas (VTPI 2015), with average auto costs around 1 cent per vehicle mile. Higher costs are estimated for diesel buses and much higher for motorcycles, while no noise costs are imposed for non-motorized modes (VTPI 2015). Electric cars are estimated to produce 30% of the noise cost of a gasoline-powered automobile in urban conditions, and 60% when driving in rural areas.

Table C-2. Estimation of Noise Cost (2007 U.S. Dollars per Vehicle Mile) (VTPI 2015).

Vehicle Class	Urban	Rural	Average	Vehicle Class	Urban	Rural	Average
Average Car	0.013	0.007	0.011	Diesel Bus	0.066	0.033	0.053
Compact Car	0.013	0.007	0.011	Electric Bus/Trolley	0.040	0.020	0.032
Electric Car	0.004	0.004	0.004	Motorcycle	0.132	0.066	0.106
Van/Light Truck	0.013	0.007	0.011	Bicycle	0.000	0.000	0.000

What Factors Contribute to the Environmental Externalities?

One can attribute the total emission in the road transportation segment across four primary categories, as noted by the Transportation Research Board (1995), including:

1. Vehicle-related factors,
2. Travel-related factors,
3. Driver behavior, and
4. Highway-related factors.

Ultimately, AVs and CVs have the potential to impact each of these factors, though it is unclear whether the net environmental result will be negative or positive, or even the potential magnitude of their effects. The following discussion outlines how each of these factors could influence environmental outcomes.

How Could CVs and AVs Lead to Desirable Outcomes?

Vehicle-Related Factors

Vehicle ownership patterns, production quantities, the types of vehicles produced, and fuel sources used all influence environmental outcomes. Recent publications, technological developments and historical precedents indicate that AVs and CVs will impact all four of these factors.

Vehicle Ownership

SAVs (SAVs, assuming L5 automation), also known as autonomous taxis (aTaxis) (Zachariah, Gao et al. 2014) or automated mobility on demand systems (AMODS) (Pavone 2015) add full driverless automation to existing car-sharing , transportation network companies, taxi, or public transportation services. SAVs open the possibility to enhance resource utilization by enabling entirely new models (Thrun 2010) and dramatically cutting travel costs (Burns, Jordan et al. 2013),(Fagnant and Kockelman 2016). Multiple studies have found that SAVs have the potential to dramatically reduce household vehicle ownership, cut travel costs, reduce parking needs, and replace many household-owned vehicles. Studies have shown that each SAV could serve the same travel needs as 4 to 12 personally-owned cars (Burns, Jordan et al. 2013, Fagnant and Kockelman 2016) (Zachariah, Gao et al. 2014), depending on service area, market penetration, ridesharing and other factors. When combined with an efficient public transportation system and enhanced cycling and walking opportunities, SAVs could be one of the building blocks of tomorrow's sustainable transport system (Sweeting and Winfield 2012). Even absent the use of SAVs, personal household vehicle usage could fall too, as L5 AVs return home to serve other household members. Sivak and Schoettle (Schoettle and Sivak 2015) estimated such a framework could cut vehicle ownership rates by 43%, though with 75% more travel generated per vehicle.

These changes in vehicle ownership patterns should also impact parking needs, and the emissions and other environmental impacts generated from parking infrastructure. With fewer vehicles needed to serve the general public's travel needs, and greater utilization of those vehicles, less parking would be required.

Vehicle Production Quantities

For both CVs and AVs (L3+), enhanced safety will likely cause a small reduction in vehicle production quantities, due to fewer crashes and thus fewer totaled vehicles in need of replacement (Johnson 2015, NHTSA 2016). Additionally, AVs (L5) present the potential for more dramatic cuts in new vehicle manufacturing and production due to changes in household vehicle ownership patterns, as discussed in the previously. Vehicles typically wear out via a combination of miles traveled and age, and more heavily used vehicles should therefore be able to incur more miles before need of replacement. For example, Stevens and Marams (Stevens and Marans 2009) estimate that Toronto taxis operate on average 248 thousand miles over their 7-year average life, significantly higher values than household-owned vehicles, which average around 25 years 152 thousand miles for passenger cars. With SAVs and household-owned L5 AVs serving more trips with fewer vehicles, production quantities could fall.

Additionally, increased ridesharing facilitated by SAVs could reduce vehicle production needs. Zachariah et al. (Zachariah, Gao et al. 2014) estimated that with full SAV market penetration, New Jersey average vehicle occupancy could rise to above 2.0 statewide, compared to an 1.69 nationally (Santos, McGuckin et al. 2011). This noted, using tighter ridesharing parameters and just 2.3% SAV market penetration, Fagnant and Kockelman (Fagnant and Kockelman 2016) estimated that less than 8% of SAV trips would be shared, indicating that market share and travel flexibility is key.

VMT changes stemming from new CV and AV capabilities should further impact manufacturing needs and resulting emissions. Potential VMT changes are discussed subsequently in this document, though it is sufficient to note here that VMT is directly related to manufacturing demands – as VMT rises, so should the quantity of new vehicles produced.

Examining these various trends, Johnson et al. (Johnson, Levy D. et al. 2015) estimated a potential reduction of up to 40% in new vehicle sales (Schoettle and Sivak 2015). While this research points towards a potential net reduction in vehicle ownership, this prognostication relies on a very high rate of ridesharing, and the ability of SAVs and family-owned AVs to last many more miles than conventional vehicles. As such, we believe that the 40% vehicle manufacturing reduction potential may be higher than will ultimately be realized.

Physical Vehicle Design and Added Electronics

The ability to untether former drivers from the task of driving may lead to new vehicle designs. As L3+ AV passengers seek more comfort, OEMs might provide vehicles with more space. Larger vehicles could serve as a mobile bedroom or office (Lamondia, D. Fagnant et al. 2016), and passengers may place greater preferences on comfort in order to accomplish work or relax while in transit (Le Vine, Zolfaghari et al. 2015).

At the same time, it is also possible that new L5 AV capabilities may lead to smaller vehicles. If purpose-built SAVs are produced, they need not be as large as a full pickup truck, mini-van, SUV, or even a regular-sized sedan. Fagnant and Kockelman (Fagnant and Kockelman 2013) found emissions savings from SAV use, much due to fleet changes from current distributions of vans, pickup trucks, passenger cars and vans, to sedan-type SAVs only. Whether L5 AV capabilities ultimately lead to increases or decreases in average vehicle size, the aspect of vehicle size has the potential to influence both manufacturing and operating emissions.

Excess power requirements from sensors and electronic equipment installed on AVs may also have negative emissions impacts. Senior research technologist James Hancock of Southwest Research Institute notes that their AVs consume around 690 watts from equipment required for automation capabilities. Even if power requirements fall as the technology matures, the power drain should still impact fuel efficiency. As a point of reference, Farrington and Rugh (Farrington and Rugh 2000) estimated that a 400 watt air conditioning load on a conventional vehicle engine can reduce fuel economy by around 1 mpg.

Fuel Type

Research indicates that AV and CV capabilities could lead to increased electric vehicle usage. For example, the AERIS Program notes that CV applications may be used to identify the location and availability of electric vehicle charging stations (USDOT 2014). Some early AV implementations have been either fully automated (e.g., Navia's driverless shuttle) or hybrid electric vehicles (e.g., Google's automated Priuses). While this does not necessarily portend an automated electric vehicle future, there are some potential synergies. For example, CAVs could sequentially and effectively utilize inductive electric vehicle charging stations without the need for drivers to return between handoffs (Jin, Fagnant et al. 2014). Chen and Kockelman's (Chen and Kockelman 2015) work notes added synergies, such as issues related to range anxiety, and charging access infrastructure, all of which could help facilitate broader introduction of electric vehicle fuel types.

Travel-Related Factors

The amount of VMT across the transportation system will invariably impact pollutant emissions and noise. Similarly, how that VMT is generated will likewise have environmental effects, as different amounts of pollutants will be emitted depending on travel patterns. The primary factors involved can be summarized here as the same ones used in a traditional 4-step travel demand model: trip generation, trip distribution, mode split, and traffic assignment (or route choice, at the individual vehicle level) (McNally 2008). This section examines how AVs and CVs could impact each of these aspects, and their resulting environmental effects.

Trip Generation

Once full automation is possible, L5 AVs will be able to provide new mobility to those formerly unable to drive. The disabled, elderly, unlicensed, and perhaps even children will realize newfound independence, thus likely increasing trip-making rates (Fagnant and Kockelman 2013). While some of these trips would likely have occurred by other modes (e.g., public transit,), AVs should help eliminate a mobility barrier for these individuals, therefore leading to more trips.

Convenience is one of the main factors that affect trip generations (Kanafani 1983), and it is likely that the perceived burden of in-vehicle travel time will fall as former drivers are freed to pursue other tasks, while reducing driver stress and increasing comfort (e.g., (MacKenzie, Wadud et al. 2014), (Gucwa 2014), (Litman 2015)). These factors should increase AV utility and convenience, improving user experiences and leading to higher trip-making rates. Additionally, CVs and CAVs should enable more efficient traffic flow and transportation system operations[8], leading to an effective system capacity increase. An elasticity-rebound effect would likely be seen in response, with other vehicles filling up the newly added capacity, and generating more VMT. Simply put, as the cost of travel falls through faster travel times, more people will travel. Quantifying these potential impacts, Cervero (Cervero 2001) estimated an urban demand-elasticity with respect to highway lane miles of 0.74.

Using similar principles, CVs and AVs could change monetary travel costs, thus impacting trip generation. CVs and/or AVs might drive more efficiently than conventional vehicles, L5 AVs could relocate unoccupied to cheaper or free parking (Fagnant and Kockelman 2016), and SAV travel could be cheaper than taxis (Fagnant and Kockelman 2016), or eventually even household-owned vehicles (Burns, Jordan et al. 2013). Yet fuel costs may increase from added electronics, as well as possible larger size (see the previous physical design discussion). SAV users may also take fewer trips, since the cost of the vehicle would be embedded in the trip, rather than a sunk cost for an already purchased car (Fagnant and Kockelman 2016). That is, the cost of a year's worth of trips via SAV trip might be cheaper than by an owned vehicle, but once the vehicle has been purchased, marginal trips could be cheaper than if taken by SAV.

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[8] For more information on this, see [49] as well as the subsequent discussion in the following section on system efficiency in this document.

In summary, while there is a good deal of uncertainty surrounding many of these trip generation outcomes, the majority of these factors point towards AVs leading to an anticipated increase in trip-making, thus producing higher VMT, more emissions and noise pollution.

Trip Distribution and Land Use

Many of the CV- and AV-related factors impacting trip generation would similarly effect trip distribution. If the burden of in-vehicle travel time falls, people would be willing to drive not only more often, but also further distances. Likewise, if enhanced system efficiency opens up capacity, people would travel not only more frequently, but also longer distances.

Assuming that generalized costs from AV and CV travel fall, AV and CV capabilities would implicitly encourage users to travel longer distances and spend more time in vehicles. This in turn could lead to increasing suburban and exurban migration, and sprawling land use. Urban sprawl has negative impacts on network performance, VMT, and total network travel times, as well as increased fuel consumption and emissions. This problem could be particularly excessive in regions with weak land use policies.

Yet SAV use could have beneficial impacts on trip distribution and land use. As noted earlier, marginal trip costs could be higher for SAV travel, even though average costs could be lower. Fagnant and Kockelman (Fagnant and Kockelman 2013) found that density (and trip intensity) was key to SAV success, and particularly crucial for ridesharing applications that increase average vehicle occupancy, and therefore cut travel costs (Fagnant and Kockelman 2016) (Zachariah, Gao et al. 2014). Therefore, SAVs could encourage higher urban density, while CVs and non-SAVs would encourage sprawl. Indeed, this may lead to a simultaneous densification of cities and exurban expansion (Economist 2016).

Mode shift

In addition to changing the number and distance of trips, AVs may alter the distribution of travel mode choices. L5 AVs will introduce a new travel mode option for many. It is possible that many of these new AV trips would be shifted from public transit, cycling or walking, due to the lack of driving ability for these users (Silberg, Wallace et al. 2012, Fagnant and Kockelman 2013, Litman 2015). These changes in travel behavior should result in increased VMT and emissions.

Moreover, one of the current advantages of public transit is the ability for transit riders to engage in activities other than driving. AVs (L3+) would remove that advantage, while providing a greater privacy level with shorter travel times than traditional transit. These advantages should increase AVs' relative utility, while creating mode shifts toward AVs and away from transit. As a result, the transportation network could experience more VMT, with worsening congestion, emissions and fuel consumption.

Introducing SAVs as a new mode could also impact VMT and associated emissions. SAV must sometimes travel unoccupied if the next passenger to be picked up is not at its current location. Without ridesharing, Fagnant and Kockelman (Fagnant and Kockelman 2016) estimated this to be around 10% of travel. Yet with ridesharing enabled, unoccupied travel could be minimized and average vehicle occupancy increased. For example, Zachariah et al.'s (Zachariah, Gao et al. 2014) previously noted 2.0 average vehicle occupancy potential for SAVs in New Jersey could have dramatic implications for VMT reduction, as well as reduced manufacturing needs. Also, in a more near-term application, SAVs could be used as low-speed demand-responsive connector/feeders to line haul mass transit systems, potentially resulting in increased transit usage (USDOT 2015). Furthermore, SAVs could reduce cold-starting emissions as SAVs constantly serve many trips throughout the day, rather than resting long periods between trips (Fagnant and Kockelman 2015). Indeed, this same effect would also be seen to a lesser degree for household-owned AVs that replace two or more vehicles.

AVs (L3+) may also influence long-distance travel mode shifts, where the driver to pursue other activities, possibility even including sleeping en-route to the destination (once the technology is sufficiently mature) (Lamondia, D. Fagnant et al. 2016). This could have negative environmental consequences, as Sivak (Sivak 2014)(Sivak 2014)[56] estimates that on a per passenger-mile basis, driving was around 57% more energy intensive than flying and 153% more energy intensive than rail travel. Furthermore, while global air pollution results from both automotive and air sources, auto travel generates local pollution along the entire route, while air travel creates local air pollution only at the origin and destination airports.

Freight too may be impacted and see shifts away from rail. With the use of cooperative adaptive cruise control (CACC), fuel savings of up to 14% could be realized by following trucks in a vehicle platoon (Tsugawa, Kato et al. 2011). Furthermore, if following trucks are not required to use a human driver (and eventually the lead truck), labor costs could be cut, leading to higher truck and lower rail utilization. Aside from the associated environmental savings from reduced fuel consumption, the mode shift component could have negative environmental consequences: Bitzan and Keeler (Bitzan and Keeler 2011) estimated that a 1% shift of US intercity freight to combined intermodal rail-truck modes could save 0.92-2.18 Tg of CO_2 on an annual basis, so a shift in the reverse direction should likely cause added environmental damages.

Vehicle Routing

CV applications should allow drivers to make more informed routing decisions in a variety of manners. Such accurate and real-time information could be used to anticipate and avoid congestion stemming from unexpected incidents, special events, and work zones, which are respectively responsible for 25%, 5% and 10% of national traffic congestion (Systematics 2005).

Other CV applications could be used to identify in real time routes that either provide the shortest travel times or lowest fuel use. While the low-fuel consumption application should result in environmental benefits, the quickest route environmental implications remain situation-dependent, contingent upon congestion, operating speeds, stop-and-go patterns, and traffic makeup on possible routes (USDOT 2014). CV applications could be used to identify available parking, resulting in substantial potential VMT savings. Shoup (Shoup 2006) found that around 30% of traffic in downtown urban areas was comprised of drivers searching for parking, and CVs paired with intelligent infrastructure could potentially cut this substantially (Berg 2012).

Driver Behavior

The following discussion outlines specific ways by which CVs and AVs may change driver behavior and the resulting environmental implications, though a more full discussion of how driver behavior will be impacted through coordination with intelligent infrastructure may be seen in the subsequent section.

Connected Eco Driving

Connected eco-driving provides customized real-time driving advice to drivers, allowing them to adjust behaviors to save fuel and reduce emissions. This advice includes recommended driving speeds, optimal acceleration and deceleration profiles based on prevailing traffic conditions, road grade, etc. Such applications may also consider vehicle-assisted strategies, where the vehicle automatically implements the eco-driving strategy (e.g., change gears, switch power sources, or use start-stop capabilities to turn off the vehicle's engine while it is sitting in congestion) (AERIS 2013).

Automated Driving

AVs may be programmed to operate more smoothly and efficiently than human drivers. It is highly unlikely that AV developers will program vehicles to drive aggressively, also the source of increased braking and rapid acceleration. Moreover, it is likely that AVs should be able to follow Eco-Driving strategies much more effectively than human drivers. In a comparison between a partially automated vehicle (using automated acceleration and braking) and a human driver, the partially automated vehicle was able to realize 22% fuel economy benefits vs. the 7% benefits for a human driver, where recommended speeds were transmitted via an in-vehicle display.

Cooperative Adaptive Cruise Control

Cooperative adaptive cruise control (CACC) is an application where two or more CAVs form a platoon on a roadway segment, with the following vehicle(s) relying receiving DSRC messages from the lead vehicle. When this information is combined with AV capabilities, CACC has the potential to reduce gaps between platooned vehicles to just a few meters, resulting in potential environmental benefits. Short spacing between vehicles allows following vehicles to draft behind the lead vehicle, reducing air resistance drag. Higher vehicle spacing density allows for a near doubling of freeway lane capacity at full market penetration. Additionally, string stability benefits may be realized, as speed variations through accelerations and braking is effectively eliminated between the platooned vehicles (Jones 2013). Eco-Cooperative Adaptive Cruise Control application (ECACC) is an extension to the CACC concept, incorporating road grade, geometry, and weather information, to determine the most environmentally efficient trajectory. One simulation study indicated 30% potential energy savings, though expected real-world energy savings may be in the 10% - 15% range (AERIS 2013).

It should be noted that the effective capacity increases realized through CACC may have either negative or positive environmental consequences. Emissions are produced at higher rates in heavily congested traffic, and effective capacity increases could relieve such congestion. On the other hand, latent or induced demand may materialize with the freeing of highway road space through CACC, leading to higher VMT, increasing sprawl and negative environmental consequences.

Roadway-Related Factors

Environmental outcomes are also dependent on the physical nature of the roadways themselves: road geometry and layout, traffic signals, network topology, and communication infrastructure. This is true for operating emissions, as well as during the construction of the facility itself. CVs and AVs look to influence roadway-related environmental impacts through adding intelligent infrastructure, while some changes may also result from reduced construction for new capacity expansion projects.

V2I Applications

CVs and CAVs may communicate with intelligent infrastructure through V2I in order to facilitate more efficient traffic flow or environmentally-friendly operation. While not comprehensive in terms of every possible V2I application with potential environmental impacts, the US DOT developed a set of environmental-focused applications for the real time information synthesis, called Applications for the Environment: Real-Time Information Synthesis (AERIS). This program is focused on five operational scenarios including Eco-Signal Operations, Eco-Lanes, Low Emissions Zones, Eco-Traveler Information (the effects of which were previously discussed in the traffic assignment section), and Eco-Integrated Corridor Management (USDOT 2014), which are discussed in the this subsection.

In the Eco-Signal operations scenario, environmental benefits may be realized through V2I communications between traffic signals and CVs. CVs could use information regarding signal phase change times or windows to provide driver guidance regarding how to adjust their speeds, with an objective of minimizing emissions (AERIS 2014). Simulation results indicate there is a potential of 5-10% improvement in fuel consumption for an uncoordinated corridor and 13% improvements for a coordinated corridor. Moreover, when an environmental-focused signal timing plan is implemented to an already well-optimized signal, an additional 5% fuel savings may be possible, at full CV penetration (AERIS 2014). Modal information communicated by CVs may also be used to improve environmental performance by giving priority transit and freight (AERIS 2014). Freight prioritization simulations have estimated 1% to 4% fuel savings for freight vehicles, depending on CV market penetration. For transit, emissions and fuel consumption may be reduced by 1% to 2%, depending on network conditions and scenario settings (AERIS 2014).

The Eco-Lanes are similar to HOV and HOT lanes, though optimized for environmental performance using CV data to real-time traffic and environmental conditions. Such lanes could be targeted towards low emission, high occupancy, freight, transit, and alternative fuel vehicles; could be utilized as CACC platoon lanes; as connected eco-driving lanes; or utilize wireless inductive/resonance charging applications (USDOT 2014). Eco-Speed Harmonization is a sub-Eco Lanes application that determines speed limits based on traffic conditions, weather information, greenhouse gas emissions, and criteria pollutant information. This application would change speed limits in advance of congestion, bottlenecks, special events, and other incidents. Speed harmonization assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds, thus reducing fuel consumption, greenhouse emissions, and other emissions on the roadway. Eco-Speed Harmonization simulation results indicate energy reductions up to 12%, with 8% mobility improvements (AERIS 2013). Combined Eco-Driving simulations using speed harmonization suggest 15% energy savings; though real world savings may be closer to 10% (AERIS 2013).

The Low Emissions Zones operational scenario seeks to restrict or deter access for high-polluting vehicles into specified geographic areas to improve air quality, while potentially simultaneously incentivizing travelers to use environmentally-friendly modes like alternative fuel vehicles or transit. Low emissions zones could leverage CV technologies to be more responsive to real-time traffic and environmental conditions. Low Emission Zone simulations at modest eco vehicle market penetration, coupled with enhanced transit service, suggest 3% to 5% energy and emission savings (AERIS 2014).

The Eco-Integrated Corridor Management operational scenario focuses on the integrated cross-agency partnering and operation of a major corridor seeking to reduce transportation-related emissions and fuel consumption. A data-fusion and decision support system is used involving multisource, real-time V2I data on arterials, freeways, and transit systems. This operational scenario includes a combination of multimodal applications that together enhance environmental outcomes (USDOT 2014).

New Infrastructure Requirements

If C/AVs are able to substantially improve system efficiency, it may be possible that fewer new capacity construction projects would be required. In 2013, U.S. states spent nearly $60 billion on interstate and arterial construction and maintenance activities. Of this, around 23% was spent on new construction and projects adding significant capacity, as shown in Table C-:

Table C-3. Aggregate U.S. State Expenditures on Interstate and Arterial Projects.

	Total Expenditures	% New Construction	% Added Capacity Reconstruction	% Major Widening
Urban Interstate	$14.90 B	4.4%	13.5%	2.6%
Rural Interstate	$6.59 B	10.5%	9.6%	4.9%
Urban Other Arterials	$13.86 B	10.3%	8.2%	4.6%
Rural Other Arterials	$22.41 B	8.5%	11.2%	4.5%

It is likely that many of these projects would still occur, due to the need for roadway rehabilitation, enhanced safety, and increased connectivity. Added capacity could still be needed in some instances, though the capacity addition portion of many projects could likely be eliminated or reduced, along with the associated emissions that such activities would produce.

In light of the prior discussion and findings, Table outlines a summary of how this research anticipates CVs and AVs may impact the various identified environmental aspects.

Table C-4. Anticipated Environmental Impacts of CVs and AVs

What are the primary factors?	What are the secondary factors?	How might CVs and AVs affect these factors?
Vehicle-related factors	Vehicle ownership	L5 AVs, particularly share use ones (SAVs), should lead to lower vehicle ownership, fewer parking needs and associated environmental costs for parking provision.
	Vehicle production quantities	Safer AVs and CVs mean fewer crashes and lower replacement rates, which would reduce vehicle production emissions. Fewer numbers of SAVs and personally-owned L5 vehicles may be needed than current conventional vehicles. This may lead to lesser production quantities and lower resulting manufacturing-related emissions. Greater AV utilization (less time between sequential trips) could reduce cold-starting emissions.
	Physical design & added electronics	AVs may be larger to facilitate comfort, or smaller to enable right-sizing, particularly for L5 SAV fleets, influencing manufacturing and operating emissions, as well as noise. Added electronics should require power, leading to more fuel consumption and operating emissions.
	Fuel Type	CV information may be used to identify available electric vehicle (EV) charging stations. SAVs alleviate EV range anxiety issues. CAVs could utilize sequential automated inductive EV charging.
Travel-related factors	Trip generation	Falling travel time burdens and latent demand from increased capacity could lead to more trips. Travel costs may fall from more efficient operation, but marginal per-trip costs could rise or fall for SAVs. Falling travel costs would contribute to increased trip generation. Those currently unable to drive will be able to travel using L4 AVs, thus incurring more trips. L5 AVs may travel empty. These factors adding more trips would produce higher operating and starting emissions, and noise.
	Trip distribution & land use	Longer trips may result from the same factors noted above for trip generation, also potentially resulting in greater urban sprawl. Empty L5 AV travel to cheap or free parking should result in longer trips. SAV use should encourage higher density and shorter trips. Longer trips should produce more operating emissions and noise.
	Mode shift	Mode shift from transit and non-motorized modes to AVs should have negative environmental outcomes. SAVs, particularly when used with ridesharing or as demand-responsive connector/feeders to mass transit systems should have beneficial environmental outcomes. Long distance travel from air and rail to AVs, and freight shipments from rail to AVs may result in negative environmental outcomes.
	Vehicle routing	More efficient routing may be used to avoid congestion and incidents. CV information may be used to identify fuel efficient routes, resulting in lower operating emissions.
Driver behavior	Connected eco driving	Customized real-time information and advice may be used to encourage optimal fuel-efficient driving behavior, thus leading to reduced operating emissions.
	Automated driving	Precise vehicle speed, acceleration and braking control, should lead to favorable environmental outcomes, as should stricter adherence to eco-driving recommendations, all of which should lower operating emissions.

What are the primary factors?	What are the secondary factors?	How might CVs and AVs affect these factors?
	Cooperative adaptive cruise control	Vehicle platoons using cooperative adaptive cruise control should see reduced wind resistance and higher fuel efficiency. Effective road capacity and improve string stability may also be realized, reducing congestion and operating emissions. However, increased capacity could lead to more trip-making or longer trips, with negative operating and starting emissions impacts.
Highway-related factors	V2I applications	More efficient operation at traffic signals enabled through communication should result in reduced delays and smoother intersection traffic flow. Dedicated managed lanes could be prioritized for environmentally-friendly operation (e.g., platooning, eco-driving, inductive electric vehicle charging, etc.). Roadway operating speeds may be used to dynamically encourage speed and acceleration profiles throughout the traffic stream. Pricing or restrictions for higher-polluting vehicles and incentives for greener modes may use dynamic real-time CV and environmental information. Inter-agency coordination of corridor management may be used to optimize corridor traffic and reduce emissions. Each of these applications has the potential to decrease operating emissions, and starting emissions in some instances.
	New infrastructure requirements	Increased effective capacity enabled through CAV capabilities may result in lesser needs for new capacity projects and lower construction-related emissions. Some new electronics may be required to enable communication.

Collectively, this work indicates that environmental externalities stemming from manufacturing, parking, and starting appears more likely to fall due mostly to vehicle-related factors, with construction emissions reductions possible through highway related factors (less new capacity construction). At the same time, operating emissions appear more likely to rise, due to travel related factors (mostly stemming from VMT increases), though some of this may be offset by system efficiency gains. While the net effects of all these factors remains quite uncertain, this framework is still quite useful for understanding how environmental impacts may be shaped.

What Actions of Producers and Consumers Would Enable These Outcomes but Might Not Be Taken Because the Societal Impacts Are External?

The above analysis is extended further by outlining stakeholder actions that may be taken and recognizing their potential impacts on environmental outcomes. We identified several actions that producers and potential consumers of vehicles equipped with AV and CV technologies can take to realize beneficial outcomes and mitigate negative ones. Several of these derive directly from the actions that producers and consumers can take to improve safety and reduce congestion, along with associated pollution.

1. Producers develop and sell interoperable V2V or V2I environmental and mobility applications

2. Producers of AVs act upon communications with road operators about infrastructure/maintenance necessary to ensure system efficiency and safe operations (across different use cases/operating conditions)
3. Producers develop and sell AVs that are lower polluting
4. Producers develop and sell AVs with eco-driving operating objectives
5. Consumers purchase vehicles with V2V/V2I capabilities
6. Consumers purchase aftermarket V2V safety applications
7. Consumers use V2V/V2I environmental, mobility, safety applications
8. Consumers are attentive to in-vehicle V2V and V2I environmental, mobility, and safety messages
9. Private shared-vehicle services operate SAVs
10. SAV operators prioritize ridesharing and linkages with line haul mass transit
11. Developers build fewer parking facilities, or build parking facilities that can be adapted to other purposes.
12. Consumers purchase AVs that are lower polluting
13. Consumers purchase AVs with eco-driving operating objectives
14. Consumers use SAVs rather than privately owned AVs which reduces their travel demand or trip generation
15. Consumers of AVs do not significantly increase overall travel demand, though the technology decreases travel cost and enables mobility among some who cannot otherwise drive
16. Consumers of AVs do not drive farther for housing, even though the technology decreases travel cost

This list represents an initial evaluation of the potential ways in which individual stakeholders can influence environmental externalities with the arrival of CV and AV technology. While this list is by no means exhaustive, it remains quite valuable as an initial starting point for understanding potential policy responses that may be taken in order to internalize the costs of environmental harms (or harm reductions) into stakeholder market decisions. Future work remains to investigate in detail such policies and actions, and to evaluate their potential effectiveness at achieving overall societal environmental goals.

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Appendix D: Land Development Briefing Paper

What Is the Land Development Externality?

Urban land development has always been influenced by transportation technologies. As U.S. cities expanded to provide housing for a growing population in the 20th century, the introduction and proliferation of the personal automobile reduced transportation costs and allowed decentralization of both residences and jobs. The personal automobile came to be inextricably linked with the suburban development pattern that dominates the American urban landscape.

While automobile travel has enabled the rapid growth of cities and their economies, it may have distorted the market for land to produce development patterns with unintended, external consequences. Land development is a complex market process: the effect of automobile use on development patterns is complicated by many market and policy factors, there is a cyclical relationship between existing development patterns and automobile use such that each may reinforce the other, and, as such, the relationship is still highly debated in academic literature. Yet current development patterns in the United States undeniably allocate a large portion of land for automobile use in the form of highways, streets and parking.

Accepting the assumption that automobile use has, to some degree, influenced the form and extent of land development in the U.S., then the land designated for vehicles can be considered an externality of driving. What are the impacts of this externality that are imposed on society as a result of automobile use? Automobile travel requires more land than other modes of travel, and while access is desirable, a marginal increase in road development comes at the expense of alternative land uses (Litman, 2015). This externality may be measured by the value of the land dedicated to automobile infrastructure that could otherwise be used for farms, open space, homes, businesses, and other facilities. Drivers impose this externality on society, with environmental, economic, and public health effects.

Sprawl is a widely used term in academic and public discourse to describe the low-density development patterns associated with car use (Burchell, et al., 2002). One view is that sprawl is inefficient, a result of policy or market failures, and generates "excessive" development beyond a socially optimal level (Paulsen, 2014). Several authors argue that automobile use contributed to development that consumes natural and undeveloped land to a greater degree than would otherwise occur (Hasse & Lathrop, 2003; Ewing & Hamidi, 2015).

There exists a library of literature on the causes, measures and consequences of land development, but it provides no consensus on whether sprawl development is inherently negative or that automobile use is its cause. Parry et al. (2007) contend that the development pattern is a result of housing taxation and zoning and development policy (Parry, Walls, & Harrington, 2007, p. 10). While Glaeser and Kahn (2003) agree that "sprawl is ubiquitous and expanding" and that driving is fundamentally responsible, the authors argue that it has generally improved quality of life[9]. Sprawl has been associated with monetary gains from lower housing costs, shorter suburban travel times (Glaeser and Kahn 2003) and the provision of lower-density living that is reflective of consumer preferences (Burchell, et al. 2002).

Despite the lack of consensus on sprawl, driving requires roadway and parking space, and much of the developed land in the United States is dedicated, often exclusively, to infrastructure for vehicles. AV and CV technologies have the potential to influence the land use patterns that contribute to the externalities of development and to change the impacts on society, depending on if and how the technologies are realized.

How Significant Is the Land Development Externality?

Land developed in the United States under the development patterns of the last century are, arguably, inefficient and may have resulted in the unnecessary destruction of forest, grasslands, and agricultural lands. Much of this land is dedicated to automobiles. A study of urban Sacramento found that 24% of developed land was occupied by roadway and 12% by parking (Hashem, et al, 2003). Manville and Shoup (2005) estimated that parking area occupies an average of 31 percent of central business districts in cities internationally (Manville and Shoup, 2005).

Delucchi and Murphy estimated the value of land devoted to public roads and right-of-way in the United States; the combined market value of road space in both rural and urban areas was an estimated $384 billion in 1991. The estimate takes into consideration the variation in the price of land by type of road, and geography (urban versus rural locations). In urban areas, the estimated price ranges from $60,000 per acre for freeways to $105,000 per acre for paved local roads (Delucchi and Murphy 1998, Revised 2003). These values suggest the potential for alternative uses of land that is now dedicated to roadways, but are complicated by the fact that land value is highly dependent on its transportation accessibility and the ecological value of undeveloped land is difficult to quantify.

Burchell et al. (2002) projected that between 2000 and 2025, 18.8 million acres of land will be converted to build 26.5 million new housing units and 26.5 billion square feet of nonresidential space in the United States. This is a conversion rate of 0.6 acres per residential unit and 0.2 acres per 1,000 square feet of non-residential space. The majority of land that would be converted is agricultural and environmentally fragile land. The authors suggest that nearly one-quarter of this land development could be avoided under a controlled, compact growth scenario (Burchell, et al. 2002). Figure D-1 presents the estimated land that would be converted under continuing sprawl development.

[9] Glaeser and Kahn (2004) do admit there may be negative consequences of sprawl: namely, the inequity between those who choose to move to the suburbs and those who are left behind, unable to afford a multi-car lifestyle.

Table ES.6
Lands Converted—Uncontrolled-Growth Scenario by Type
United States and by Region: 2000 to 2025

	Uncontrolled-Growth Scenario				
Region	**Total Land (Acres)**	**Percentage of Overall Land (%)**	**Agricultural Lands (Acres)**	**Environmentally Fragile Lands (Acres)**	**Other Lands (Acres)**
Northeast	1,460,868	7.8	292,067	1,063,293	105,508
Midwest	2,789,832	14.8	1,750,966	646,016	392,850
South	9,969,932	52.9	3,605,201	4,468,081	1,896,650
West	4,612,290	24.5	1,443,842	866,835	2,301,613
United States	18,832,922	100.0	7,092,076	7,044,225	4,696,622

Source: Center for Urban Policy Research, Rutgers University.

Figure D-1. Lands Converted in Sprawl Development Scenario.

The recognition of the ecological role of forests, wetlands and prime farm lands has led to greater concern for the loss of these lands to development. A study of development in New Jersey from 1986 to 1995 found that on average 0.57 acres of land was consumed per new resident: 0.12 acres of prime farmland, 0.25 acres of forest core habitat, 0.05 acres of natural wetlands and 0.12 acres of impervious surface were created (Hasse and Lathrop 2003). While the amount of land dedicated to development is relatively small in comparison to the abundant lands available in the United States (for instance, forest cover has increased in recent decades), protecting fragile natural resource lands is increasingly a goal (Hasse and Lathrop 2003). Furthermore, the future value of protecting environmental ecosystems may be undervalued today.

The term sprawl is frequently used to describe the land development patterns common across the United States (Burchell, et al. 2002). Yet the term lacks a consistent definition. Lower density development (relative to older central cities) is typically a defining feature of sprawl. Other authors suggest more nuanced, multidimensional explanations (Paulson, K., 2013). Sprawl is frequently defined by (a) non-contiguous, leapfrog or scattered development, (b) commercial strip development, or (3) large expanses of low-density or single-use development (Ewing & Hamidi, 2015). Zoning generally segregates residential, commercial and industrial land uses and roadway design prioritizes travel by automobile, sometimes at the expense of other modes (Parsons Brinckerhoff Quade & Douglas, Inc. 1998).

Burchell et al (2002) summarize the impacts of sprawl in five major areas of concern: "(a) land losses; (b) capital infrastructure costs for roads and water/sewer; (c) transportation impacts, (e.g., vehicle miles traveled and automobile versus transit use); (d) quality of life related to measures of satisfaction of place under sprawl, yet dislike of its visual outcome; and (e) social impacts related to the spatial mismatch of jobs/workers and the decline of urban tax bases." (Burchell, et al. 2002).

The external costs of sprawl can be measured by comparing the consequences of sprawl development to alternative uses of the land; researchers often compare existing development patterns to more compact, less resource-intensive development. Various studies have found that the costs of sprawl development are greater than the costs of more compact development. Burchell et al. (1992-1997) found that 20% to 40% of agricultural land consumed by "business as usual" sprawling development could be averted with compact development. Landis (1995) found that nearly 50% of farmland acreage and 100% of wetland areas near San Francisco could be saved under a compact growth scenario (Parsons Brinckerhoff Quade & Douglas, Inc. 1998, 66). Duncan (1989) found that sprawl developments in Florida spent 60% more funding on roads than compact developments (Parsons Brinckerhoff Quade & Douglas, Inc. 1998, 41).

Figure D-2 summarizes the results of several studies comparing the costs of sprawl and compact development as reported by Parson Brinkerhoff in *The Full Costs of Alternative Land Use Patterns*. This review of previous research found that "land consumed under sprawl has almost always been shown to be more than land consumed under compact growth patterns." (Parsons Brinckerhoff Quade & Douglas, Inc. 1998, 51).

		Compact Development Costs as Percent of Sprawl Development Costs: Findings from Three Major Studies			
Infrastructure Cost Category	Sprawl Development	Duncan Study (1989)	Frank Study (1989)	Burchell Studies (1992-1997)	Compact Development Costs: Synthesis from Three Major Studies (in percent, relative to sprawl)
Roads (local)	100%	40%	73%	74-88%	≈75%
Schools	100%	93%	99%	97%	≈95%
Utilities	100%	60%	66%	86-93%	≈80%

Source: Burchell and Listokin (1995) and Table 4

Figure D-2. Study Findings on the Relative Costs of Sprawl Versus Compact Development. (Parsons Brinckerhoff Quade and Douglas, Inc. 1998).

Land dedicated to parking is another aspect of how sprawl development contributes to the excess development of land. Cahill et al. (2016) found that an increase in parking provision results in an increase in automobile commuting (McCahill, et al., 2016). Donald Shoup (2005) argues that parking minimum requirements contribute to the unaccounted external costs of driving. Off-street parking requirements, common in central cities, may help reduce local congestion (circling to find a spot) and facilitate automobile access to the services offered in business districts. However, these parking requirements prevent alternative investments that could have financed higher value development in those locations while incentivizing firms and developers to locate in places where land is less expensive. In other words, if parking requirements are applied uniformly across a city, the burden of compliance is higher where land costs are more expensive and more development is pushed to undeveloped land (Shoup, 2005). As such, the dedication of land to parking may both decrease the density of development in central cities and exacerbate the lower-density development on the urban fringe as developers try to offset parking development costs with lower land prices.

What Factors Contribute to the Land Development Externality?

Land development is a complex process that is influenced by household preferences, economic trends, and development, housing and transportation policies. Much debate currently exists as to the relative influence of various factors that contribute to development patterns and the degree of impact of these factors. Some factors, such as population growth, are a clear driver of urban growth but do not inevitably lead to sprawl. Most people would agree that some amount of development is necessary to meet housing needs. Other factors, such as preferences for low density housing are difficult to isolate from federal and local policies that influence the housing market. Factors that have influenced land development patterns in the United States can be divided into two categories – market forces and public policy decisions.

Market Forces

Land development is driven by the demand in the market for housing and employment activities. The price of a plot of land reflects the potential development value of that land; centrally-located land tends to be assigned more worth than more remote, undeveloped land. As cities grow and roads are constructed, land on the urban edge gains value for potential development while maintaining a relative price advantage over higher-priced central land.

Households, businesses and developers make decisions about land, housing, and office space based on the costs and trade-offs presented in the market. This can include population growth, household composition, residential preferences, transportation costs, and commute preferences. Together, these decisions are reflected in our development patterns. However, land markets are not perfect markets –pricing is subject to speculation, all costs are not fully internalized and government policies alter the market (Ewing, 2008).

Public Policy

Federal and local government policies related to land use, zoning, transportation and homeownership have created market distortions that impact land development and, in some cases, contribute to sprawl. Local development regulations that discourage higher density development push development outward instead of upward. Development policies have been found to undercharge consumers and developers for the costs of infrastructure (e.g. sewers, parks) which subsidizes new, remote development. Zoning ordinances segregate land uses and thus increase dependence on automobile travel. Building requirements, such as those that dictate setbacks and lot size, are argued to interfere with the land and housing markets and produce inflexibility in building types (Ewing and Hamidi, 2015).

Public spending at all levels of government to build and maintain highways and roadways for automobile use is argued to amount to a subsidy for the automobile. This along with the relatively low gas tax and insufficient spending on public transit is another factor that contributes to the growth of sprawl (Glaeser and Kahn, 2003).

Suburban homeownership has been implicitly subsidized by tax policies including property tax and mortgage interest deductions and federally-insured loans (Ewing & Hamidi, 2015). These policies increase the amount of housing that people are willing to consume and favor single family home development outside of urban areas.

How Could CVs and AVs Lead to Desirable Outcomes?

While there is agreement that the current urban landscape in the United States is automobile-oriented, there is uncertainty as to whether or to what extent automobile use is responsible. CV and AV technologies have the potential to change the externalities of land development by altering factors that contribute to current land use development patterns. There is even more uncertainty surrounding the changes that may occur as AV and CV technologies enter the market. Some of the potential links between AVs and CVs and the market and policy factors that influence land development patterns are discussed in this section.

Transportation Costs

Transportation costs – both monetary and non-monetary – currently moderate the distance one is willing to travel to access lower-priced land for development. Automobile availability greatly increased mobility and improved accessibility outside of the central city core (Glaeser and Kahn 2003). As with the introduction of the automobile, AVs and CVs have the potential to decrease the non-monetary costs of driving.

CVs are primarily designed to provide safety benefits but may also reduce congestion, increase mobility and improve the driving experience. V2V and V2I technology can provide safety warnings that mitigate crashes and enable communication between vehicles to improve efficiency (make better use of roadway space) and reduce congestion caused by bottlenecks, work zones and weather.

AVs may also contribute to increased efficiency of the vehicle and greatly reduce the burden of driving, especially as the driver is progressively able to disengage from the driving task with higher levels of automation. If fully-automated Level 5 AVs were allowed to drive with no human driver present in the vehicle, time and other non-monetary costs of vehicle travel would be further diminished. Owners could send vehicles on pick-ups or to accomplish errands or to return home empty after dropping a passenger off, without having to devote time or energy to the trip. An AV equipped and allowed to drive unoccupied and return home after each trip may more easily allow shared among household members, which could lead to a decrease in the number of vehicles per household. Sivak and Schoettle (2015) estimated this could reduce average vehicle ownership rates by 43 percent. However, the authors also conclude that travel per vehicle would increase by 75 percent (Schoettle & Sivak, 2015). This suggests that individual vehicle costs may decrease, but the impact on land development is uncertain.

Lower transportation costs provided by CVs and AVs and a continued demand for lower-density housing may encourage development on rural, lower-cost land. Given the slow turnover of vehicle fleets and the likelihood that AVs and CVs will come at a high price, at least initially, any potential impact on land development will only occur in the long term. Furthermore, these benefits depend on industry and government implementation as well as consumer acceptance and adoption. In the short-term, increased safety and an improved driving experience are likely to continue current trends in land development.

Travel Mode Preferences

Automobile travel is already the selected mode choice for most travelers in the United States. CVs and AVs offer potential safety and convenience benefits that could further drive preferences for automobile travel. If drivers can accomplish other tasks while driving AVs, the relative convenience and comfort of driving would increase. However, transit, biking, and walking modes may continue to be preferred for health and environmental benefits.

The safety, congestion and improved driving experience offered by CVs could similarly continue or increase the current market demand for automobile travel. It is possible that fully-automated AVs requiring no driver input will enable previous non-drivers, such as the blind and unaccompanied children, to join the pool of potential drivers (Smith 2012). This could increase the overall demand for driving and automobile-oriented development.

On the other hand, the combination of high level AVs with existing concepts of car-sharing, ride-sharing, and public transportation could introduce shared autonomous vehicles (SAVs) to the market. This suggests a potential for AVs to contribute to a shift away from personal vehicle ownership to shared fleets. SAVs could contribute to better utilization of vehicles (that currently spend most of a day idle) and decreased travel costs (Fagnant & Kockelman, 2016).

Future trends in ride-sharing and ride-sourcing services, epitomized by Uber and Lyft, will thus be a factor in how AVs affect driving trends. If advanced vehicles are introduced through shared fleets then car ownership levels may decline. This is a reasonable trajectory for AV because shared-vehicles facilitate more trips per day than a private vehicle, better justifying a higher purchase price of an AV. Removing the cost of driver labor from taxi or ride-sourcing exchanges could also lower the cost for customers. It is unclear how this would impact driving: Automated shared fleets could decrease the number of trips made by vehicle as well as dampen VMT growth, as travelers pay based on the marginal cost of each additional mile traveled, or increase vehicle travel due to the same benefits attributed to personal AVs.

Highway Funding

Government spending to build and maintain highways and roadways arguably subsidizes automobile use and encourages excessive land development. Nearly $60 billion was spent by U.S. states on interstate and arterial construction and maintenance activities in 2013. Nearly one-quarter of this was spent on new construction and added capacity reconstruction. CVs and AVs may change roadway capacity and maintenance needs as well as reduce transportation revenue from the gas tax.

CVs and AVs offer potential increases in system efficiency, creating capacity for more vehicles in a given amount of roadway, and lowering demand for future highway expansion. CVs are designed to increase system efficiency by alerting drivers to hazards, advisories and weather issues that would otherwise impair travel. Studies of AVs have shown that adaptive cruise control and traffic monitoring abilities could smooth traffic flow, increase fuel economy and increase traffic speeds (Fagnant and Kockelman, 2013). While some expansion may still be necessary, capacity increases and efficiency gains due to CV and AV technology may reduce the need for expansion. However, induces travel due to CVs and AVs may exacerbate roadway maintenance costs and the technological requirements of CVs may shift government spending to technology and computing infrastructure needs.

The rapid expansion of automobile-oriented land development is also argued to be a result of the relatively low and stagnant gas tax in the United States. CVs and AVs have the potential to increase fuel efficiency of vehicles through traffic smoothing, congestion reduction and, for CVs, synchronization among vehicles. Smart parking applications could also improve fuel economy (Fagnant and Kockelman, 2013). The implications of increased fuel economy are already being seen in the increase in electric, hybrid and fuel-efficient vehicles. CVs and AVs may contribute to this effect, further decreasing drivers' tax burden, and decreasing transportation tax revenue, but there is no evidence suggesting they will change the current trends.

Parking Policies

Parking effects will be experienced differently in urban and rural areas. In urban areas, AVs may reduce the need for parking adjacent to destinations. AVs and CVs may be able to park in smaller spaces with more precision than human drivers, and higher level AVs are expected to have the ability to drive and park at home or in remote parking areas. This would allow for more cars to fit in less space and in non-adjacent locations to free up centrally located land for other uses. In a shared-vehicle scenario, a vehicle could attend to other trips after dropping off a passenger – reducing the need for parking at each destination. Changes to parking needs will only occur with high levels of AV/CV adoption and would require changes to the parking requirements, which currently mandated parking minimums for new development. In the long term, this may stimulate infill development as existing parking infrastructure in high-rent areas is no longer needed. In contrast, in rural areas the unbundling of parking adjacent to activity centers could lead to the construction of parking on cheaper, undeveloped land – following the same patterns seen with previous sprawl development.

Land development, characterized by low-density automobile-oriented development patterns, is often linked to the excessive development of rural, agricultural and fragile environmental lands. Automobile use enables access to undeveloped rural and remote areas more rapidly and at a low cost to consumers, and in turn, leads to land development that exacerbates auto dependence. This may result in external costs of development that could be reduced or avoided with more controlled, compact growth. The introduction of AV/CV technologies into the vehicle market has the potential to change transportation costs, travel preferences and a reevaluation of public policies that lead to sprawl. The effect of CVs and AVs could exacerbate the automobile dependence that defines sprawl development, as driving becomes even more efficient, safe and convenient. On the other hand, the potential for SAV fleets or a shift away from personal vehicle ownership models could lead to decreased vehicle travel and increased density development in high-value land no longer required for parking. Since land value and development decisions are the result of many complex factors, it is yet unclear exactly how the introduction of AV/CV will impact either.

Factors that influence land development patterns are summarized in Table D-1.

Table D-1. Effects of CV and AV on Causes of Land Development Patterns.

Type of Factor	What are the factors?	How might CVs and AVs affect these factors?
Market Forces	Population growth	We do not anticipate that CVs or AVs would impact population growth
	Household composition	We do not anticipate that CVs or AVs would impact household composition
	Residential housing preferences	We do not anticipate that CVs would impact housing preferences directly.
	Transportation Costs	CV/AVs could increase safety and convenience of vehicle travel, lowering transportation costs. CVs may increase system efficiency and lower costs: unclear impact on excessive, auto-oriented development AVs may reduce the non-monetary costs associated with driving, allowing consumers to travel more miles and take more trips in order to access lower priced land and rural locations.
	Travel mode preferences	AV/CVs may increase the safety and convenience of driving, continuing the preference for automobile travel and possibly leading to an increase in use. If the technology is incorporated into transit vehicles and shared vehicles, the effect would be opposite – decreasing vehicle ownership and use in favor of transit and shared mobility.
Public policy decisions	Development policies	We do not anticipate that CVs or AVs would impact development policies or zoning ordinances
	Highway Funding	AVs and CVs may change funding needs from capacity and maintenance to technology. Changes to tax policy are not expected, and so introduction of AV/CV will not drastically change the resulting behavior of drivers.
	Parking policies	AVs may reduce the need for parking adjacent to destinations, which is currently mandated though parking minimums for new development. Parking requirements currently placed on developments may be altered or eliminated. Parking in urban areas may be reused for other land uses while parking development may be shifted to rural areas.
	Home-ownership incentives	We do not anticipate that CVs or AVs would impact homeownership incentives

What Actions of Produces and Consumers Would Enable These Outcomes but Might Not Be Taken Because Societal Impacts Are External?

We identified four actions that producers and potential consumers of vehicles equipped with AV and CV technologies can take to realize beneficial outcomes and mitigate negative ones:

1. Consumers use SAVs rather than privately owned AVs which reduces their travel demand or trip generation
2. SAV operators prioritize ridesharing and linkages with line haul mass transit
3. Consumers use Level 5 vehicles to avoid parking in urban centers.
4. Developers build fewer parking facilities, or build parking facilities that can be adapted to other purposes.

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Appendix E. Mobility for Aging Adults and Individuals with Disabilities

What Is the Mobility Externality?

Access to transportation is essential for a high quality of life for nearly all Americans, yet is often a significant challenge for aging adults and individuals with communicative, mental, or physical disabilities. Many live in car-dependent areas but do not drive, and transit alternatives may be geographically inconvenient or inaccessible. The Americans with Disabilities Act (ADA) mandates that transit authorities operating a fixed route system provide paratransit or a comparable service to individuals with a disability (U.S. Department of Justice, 2016). ADA paratransit is a high demand alternative, but the average cost of a trip for passengers is almost twice as expensive as the same fixed-route transit trip (Government Accountability Office, 2012).

The lack of mobility has serious consequences. Individuals with disabilities cite the lack of transportation options as a structural barrier to accessing health care (Drainoni et al., 2006). Aging adults who stop driving may not only face a decrease in quality of life, but may also experience symptoms of depression (Frye, 2013; Marottoli et al., 1997; Metz, 2000). In isolated urban and rural environments, driving may be the only option for transportation where public alternatives or pedestrian access are unavailable (Frye, 2013).

The limited mobility of aging adults and individuals with disabilities can reasonably be viewed as a negative externality of the existing transportation system, which strongly favors transportation in personal automobiles. Consumers who own and operate a vehicle do not internalize the full cost of their cars due to a variety of explicit and implicit driving subsidies (Crouse, 2000; Litman, 1997). One example is public investment in infrastructure directed to the design of communities that tend towards urban sprawl. Local and regional authorities have at times expanded roads and highways as a means to optimize commuting times in lieu of public transportation infrastructure that requires extensive resources and economies of scale to function (Glaeser & Kahn, 2003). These policies have amplified the mobility challenges of non-drivers and decreased the resources available to fund alternatives that would address their needs (Glaeser & Kahn, 2003; Williams, 2010).

Indirect subsidies for vehicle owners manifest themselves in the form of income tax exceptions towards fringe benefits for employees who are able to park for free at their place of employment, as well as zoning requirements that typically require large quantities of parking for residential and commercial development (Delucchi & Murphy, 2008). The artificially low cost of driving reinforces the preeminence of private vehicle ownership and use when public and private transportation resources are prioritized. This creates a mobility ecosystem in which the cost effectiveness of purchasing a motor vehicle is greater than that of other modes of transportation.

The benefits to automobile drivers come at the expense of the mobility of those who cannot drive or lack other transportation options. Within this group, aging adults and individuals with a disability are a vulnerable population and their challenge in securing travel becomes an externality of the status quo. In the words of David Crouse (2000):

> *"Over the long term, underpriced driving increases automobile dependency: land-use patterns become more dispersed, which increases mobility requirements, and consumers have fewer lower-priced travel choices. This is disadvantageous to…non-drivers and therefore vertically inequitable."*

The existing transportation infrastructure does not completely address the limited mobility of this population. Autonomous and connected vehicles (AV and CV respectively) represent an opportunity to reduce this externality, possibly even eliminating it (Bradshaw-Martin & Easton, 2014). By leveraging the existing infrastructure that favors motor vehicles, AVs at the highest level of automation (SAE L4-5) can complement current alternatives to empower aging adults and individuals with disabilities to fully engage with their surroundings.

How Significant Is the Mobility Externality?

The literature does not offer estimates on the cost of this externality. However, the number of individuals affected and the expenditures on paratransit suggest that it is significant: it affects tens of millions of people and costs many billions of public dollars annually.

Aging adults

The population of Americans over the age of 65[10] was 43.1 million in 2012 and is projected to increase to 83.7 million in 2050 (Ortman, Velkoff, & Hogan, 2014). A contributing factor to the shift in the country's population pyramid for the next several decades will be caused by individuals born between 1946 and 1964, also known as baby boomers (Hogan, Perez, & Bell, 2008). Although in 1999 this generation peaked at 78.8 million individuals, their numbers have grown through 2010 with the arrival of migrant contemporaries (Colby & Ortman, 2014).

To understand the factors of mobility that impact this population, it is necessary to examine the voluntary and involuntary causes of driving cessation (Choi, Mezuk, & Rebok, 2012; Oxley & Whelan, 2008). A voluntarily decision represents an acknowledgement that the skills required for this activity are no longer available and some studies report that it is likely responsible for most cessation (Choi et al., 2012). This can manifest itself via the self-imposition of a restriction to drive at night, which is done by three quarters of aging adults with disabilities over the age of 75 (compared to 54% of their peers without a disability) (U.S. Department of Transportation, 2003).

Involuntary driving cessation has its roots in a medical condition or loss of privileges (e.g. unable to renew a driver's license). In effect, Table E-1 presents data on the percentage of

[10] The age of 65 years is not implied as an age of declining driving capability necessarily, but provides a sense of the aging U.S. population who may be faced with future years of declining mobility.

Americans over the age of 50 that drive and the proportion that have a disability that limits this activity. On the one hand, disability is a major factor in limiting driving in adults as they age. According to estimates by Foley et al (2002), 600,000 adults over the age of 70 stop driving each year and individuals that suffered a temporary or ongoing limitation where among the most likely to stop doing so.

Table E-1. Mobility of Aging Adults (2009).

Age group	% drivers	% with disability*
50-59	93.7	10.9
60-69	91.4	15.8
70-79	83.0	22.6
80 and aging	61.7	41.3

Source: (Santos, McGuckin, Nakamoto, Gray, & Liss, 2009)

* Percent with disability is based on respondents who answered that they had a temporary or permanent condition that makes it difficult for them to travel outside of the home.

On the other hand, qualifying for a license may preclude aging adults from legally driving. All drivers' licenses in the U.S. expire and need to be renewed in a delimited amount of time according to local regulations (these range between two and eight years). Many States have provisions that scrutinize this population at renewal via the requirement of an eye exam, skills exam or a certificate from a physician that establishes their fitness to drive (e.g. Arizona, Colorado, and Maryland) (AAA, 2016).

Other factors that may contribute to mobility limitation in this population include geographical and income characteristics. Approximately 80 percent of the 45 million Americans over the age of 65 live in car-dependent locations and nearly 90 percent wish to age in place (Dudley, 2015). Geographical location, particularly the population trend where youth migrate to urban and more dense counties, has increased the proportion of aging of adults in rural counties (Jones, Kandel, & Parker, 2007). Compared to their counterparts in urban areas, rural aging adults face a lack of transportation infrastructure that may affect their ability to perform daily activities (J. E. Burkhardt, McGavock, Nelson, & Mitchel, 2002).

Income can be considered a determinant of mobility because resource availability constrains the ability to purchase a new vehicle, maintain it, or live in a neighborhood connected to different modes of transportation (J. E. Burkhardt et al., 2002). A study by Ragland et al (2004) found evidence to this effect concluding that "household income was a significant predictor of reasons to limit or avoid driving" among aging adults. The relevance of this finding is highlighted by the fact that an estimated 10% of the population over the age of 65 (4.6 million) are below the poverty line (DeNavas-Walt & Proctor, 2015).[11]

[11] The U.S. Census Bureau defines poverty on a scale that varies by family size and age. For single individuals over the age of 65 the threshold is $11,354 and for couples over the age of 65 it is $14,309.

Individuals with disabilities

In the 2010 Census, 56.7 million individuals identified as having either a communicative, mental or physical disability (18.7% of the total population). Out of this group, 38.3 million (12.6%) reported a severe disability such as being unable to perform activities of daily living without assistance (e.g. going outside the home, dressing, eating), being deaf, blind, among others (Brault, 2012).

Insights into the mobility of this population are explored in the National Transportation Availability and Use Survey (NTAUS) developed by the U.S. Department of Transportation (2003). In terms of vehicle ownership, individuals with disabilities are three times more unlikely than individuals without disabilities to own or lease a vehicle (12.58% vs. 4.40%). Ownership of a vehicle does not equate to actively driving it, thusly around 35% of the individuals that are disabled do not drive, while the proportion of individuals without disabilities that also don't is 12%.

The prevalence of public transportation use at least three or more days per week among this group was higher than their counterparts without a disability (42% versus 28%). However, they expressed having a harder time than their peers without disabilities in obtaining the transportation they require to be independent (12% versus 3%) and the top two reasons given for this were: no or limited public transportation (33%) and not having a car (26%).

Overall, the experience of using public transportation varies by location, since not all local authorities have equipped or maintained infrastructure that caters to the needs of this population (Thatcher et al., 2013). For instance, the lack of disability access for bus stops or inoperable service elevators challenges daily mobility. Table D-2 provides evidence of the discontent felt by this group compared to those without a disability. It shows that in most modes of transportation, having a disability makes the experience of difficulties more likely.

Table E-2. Percentage of the Population That Experiences Problems with Local Transportation.

Type of transportation	% with disability	% without a disability
As a pedestrian	48.60	36.75
As a cyclist	40.15	35.23
At bus stops	41.77	33.99
On a bus	31.91	23.15
At subway/light rail/commuter train stations	36.46	38.02
While on the subway/light rail/commuter trains	33.64	26.00
Public paratransit service	29.42	34.09

Source: (U.S. Department of Transportation, 2003)

Cost of the externality

Limited literature is available that measures the cost of the mobility externality imposed on aging adults and individuals with a disability. However, an examination of the resources spent by public authorities to facilitate the transportation of this population shows that the costs may be significant.

A proxy for the resources devoted to the population examined in this section can be found in the legislation of the Americans with Disability Act (ADA) in 1990. Data on ADA compliant services is available via a survey performed by the Government Accountability Office (2012) whose results are generalizable to transit agencies that provide demand-response services. It found that between 2007-2010 agencies experienced an increase in the demand for trips (7%) and registration of the individuals eligible for complementary paratransit (12%). Each one of the paratransit trips cost authorities on average 3.6 times more per passenger than those taken on fixed-route transportation modes ($29.30 vs. $8.15).

The size of the public transportation system appears to make a difference in the cost of these services. For instance, large systems tend to spend more resources on each ADA trip compared to medium and smaller counterparts, $42.23 vs $28.94. However, larger transit systems expend fewer resources per fixed-route passenger trip than smaller transit systems, $3.82 vs. $8.24. The ability of these systems to recoup the costs of providing such services is restricted by the ADA. According to the legislation, transit authorities may charge paratransit customers no more than twice the average fare for fixed-route alternatives. This has resulted in the average paratransit fare to be $2.09, while the same for fixed-route modes was $1.13.

The Federal government has made available resources to facilitate the payment of services targeted to individuals with limited mobility; this includes aging adults, individuals with disabilities, individuals that live in rural counties, among others. In 2012, the Government Accountability Office (2013) identified 80 such initiatives that either directly or indirectly facilitated transportation services for this population. One such program was the Federal Transit Administration's Enhanced Mobility of Seniors and Individuals with Disabilities program, which granted $257 million in the 2015 fiscal year (U.S. Department of Transportation, 2015). A challenge in quantifying the total resources allocated to this function is that not all programs track transportation spending. Thus, budgetary information was available only for the 28 programs that reported expenditures and this equaled $11.8 billion for the 2010 fiscal year.

In 2010, Koffman et al (2010) estimated that the projected demand and cost of all publicly provided services for this segment would grow over the next 20 years (Table 3). An adequate mix and level of service would equate to a yearly investment of $4.7 billion from 2010 to 2020, $6.3 billion from 2020-2030, and $8.6 billion from 2030 onwards in operation and capital costs.

Table E-3. Projected Demand for Public Transportation.

Service type	Annual Trips (millions per year)		
	2010	2020	2030
ADA Paratransit	54.3	71.5	95.5
Dial-a-Ride	100.7	126.3	178.3
Taxi Subsidy	13.6	18.0	24.4
Volunteer drivers	20.5	27.9	36.4
Community Buses	28.2	37.9	57.7
Total	217.2	281.7	392.5

Source: (Koffman et al., 2010)

What Factors Contribute to the Mobility Externality?

We identified three important factors that contribute to the limited mobility of aging adults and individuals with disabilities:

1. **Limited availability of alternative transportation modes:** As noted, approximately 80 percent of retirement-age adults live in car-dependent communities (Dudley, 2015). In isolated urban and rural environments, driving a car may be the only option for transportation for the elderly and disabled where public transportation alternatives or pedestrian access are unavailable(J. Burkhardt, Berger, & McGavock, 1996; Frye, 2013). The top reason given by individuals with disabilities who reported having difficulty obtaining transportation was no or limited public transportation(U.S. Department of Transportation, 2003).

2. **Difficulty using alternative modes:.** Research shows that individuals with disabilities are significantly more likely to experience difficulties using transit than those who do not – 32% vs 23% on buses, for example (Thatcher et al., 2013). While paratransit may provide an alternative, this may not be available to everyone. For instance, aging adults with frailty or chronic conditions may not be able to use transit, but may also not be eligible for ADA-related paratransit (Bailey, 2004).

3. **Cost of driving and other transportation modes:** Income is a determinant of mobility because it affects the ability to purchase a new vehicle, maintain it, or live in a neighborhood connected to different modes of transportation (J. E. Burkhardt et al., 2002). As noted, paratransit can costs, on average, up to twice as much as fixed-route services. These costs can be prohibitive for aging adults and individuals with disabilities. In 2014, 28.5% of individuals with a disability and 10% of aging adults have a yearly income that is below the poverty line (DeNavas-Walt & Proctor, 2015).

Note that these are not *all* the factors that contribute to the mobility challenges. There may be social, economic, and other reasons. However, these are the factors we have concluded to be most relevant for a discussion of the externalities of AVs and CVs.

How might AVs and CVs Create Desirable Outcomes?

The introduction of L5 AVs in the future has the potential to improve the accessibility and availability of transportation (Anderson et al., 2014). The extent of this benefit depends on two key factors: usability and cost.

Individuals must be able to use L5 AVs. Individuals who are otherwise independent, e.g., aging adults that have voluntarily stopped driving and individuals with non-severe disabilities are likely to experience the fewest barriers to use and greatest gains. For those that live in geographically dispersed areas, they offer mobility alternatives that are unavailable because of their socioeconomic status or their cost inhibits investment from the public sector for the provision of such services (Frye, 2013). They can also actively participate in society via seeking new career opportunities that would otherwise be hindered by the lack of reliable transportation (J. Burkhardt et al., 1996).

Yet, for many elderly and individuals with disabilities, the costs of a personally owned vehicle are prohibitive; the costs of an AV even more so. Shared models of use – through either private shared mobility providers or transit – may offer affordable ways of increasing mobility at affordable cost.

The benefits of conditional automation (SAE L3) and CVs on this population are unclear. The concern with this level of technology is the expectation of human intervention with passengers that may not have the capabilities to operate a vehicle, which can lead to liability issues (Henderson & Golden, 2015; Mele, 2013). In an event of an accident, the ability to discriminate between an error made by the vehicle or the human may require complex authentication or verification systems to verify the party at fault. Precedents in the application of liability in the judicial system may not favor manufacturers, as courts sometimes impose responsibility on products that cause physical harm as a result of breakdown of navigational equipment (Mele, 2013).

Another issue to consider with conditional automation is the lack of a regulatory framework for granting a population with limited mobility, specifically individuals with a disability, with permission to control a vehicle. In the U.S., four states and the District of Columbia have created legislation to permit the use of AV, but in most cases a licensed driver must be present and able to intervene in its operation (Kalra, Anderson, & Wachs, 2009; Smith, 2014). This standard potentially excludes aging adults and individuals with a disability, more importantly it shines light on the procedural void for assessing the basis for which fitness to drive is determined (Carr & Ott, 2010). Internationally, fundamental issues of what defines a driver need to be rethought as well, such as how the Geneva Convention on Road Traffic, which the US has ratified, defines a driver as:

"any person who drives a vehicle, including cycles, or guides draught, pack or saddle animals or herds or flocks on a road, or who is in actual physical control of the same" (Bradshaw-Martin & Easton, 2014; United Nations, 1949).

Individuals with severe disabilities and aging adults that have involuntarily lost their mobility independence can realize benefits from AVs and CVs to the extent that they are able to receive assistance when using the technology. In this sense, users may not need to provide instruction to a SAE L5 vehicle, but they can face barriers in entering it. In the same manner, this population may not be able to provide a SAE L3-4 vehicle with the feedback required for operation.

What Actions of Producers and Consumers Would Enable These Outcomes, but Might Not Be Taken Because the Societal Impacts Are External?

We identified five distinct actions that producers, providers, and potential consumers of L5 vehicles can take to realize these beneficial outcomes:

1. Producers develop and sell Level 5 vehicles that are usable by aging adults and individuals with disabilities
2. Private shared-vehicle services purchase Level 5 vehicles and operate them at affordable prices
3. Aging adults and individuals with disabilities (consumers) purchase Level 5 vehicles
4. Aging adults and individuals with disabilities (consumers) use Level 5 paratransit or shared services

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