Climate and Energy Impacts of Automated Vehicles

Prepared for the California Air Resources Board

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Executive Summary

Automated vehicle (AV) technologies are developing rapidly and nearing widespread adoption, with consequences for energy use and greenhouse gas (GHG) emissions. This report provides a resource for the California Air Resources Board (ARB) to understand AV technologies and monitor their evolution.

The principal public interest in AVs is an improvement in safety. At the state level, the California DMV and, to a lesser extent, Caltrans are the lead regulatory bodies for AVs as they begin to appear on California's roads. The ARB, which regulates and promotes clean vehicles and vehicle fuels, is an interested party in the AV discussion with the perspective of promoting AV development in a manner consistent with the state's climate goals.

As of 2014, the adoption pattern for AVs is evolving and uncertain. Barriers exist in technology development, cost, regulatory needs and public acceptance. Optimists argue that AVs will be widely available by 2020 or 2025 at the latest, while pessimists say that significant market penetration is decades away. Adoption of hybrids and electric vehicles provide some clues: it has been nearly twenty years since the Toyota Prius was first introduced in Japan, and market penetration of alternative fuel vehicles is limited, though growing, especially in California. Nevertheless this comparison should not be overstated as AVs may represent a very different technology shift.

AVs have the potential to deliver enormous gains in safety, but climate impacts of AVs are, at this point, ambiguous. Overall impacts depend on adoption patterns, which at present remain unclear. Preliminary estimates cover an extremely wide range; Exhibit ES-1 summarizes theorized climate impacts of AVs. On the positive side, efficient driving could yield significant fuel savings and reduce congestion. However, AVs would reduce the cost of driving and could contribute to an increase in travel demand unless carsharing becomes widespread.

Exhibit ES-1: High-level summary of AV Climate Impacts

Impact	Mechanism	Outcome
Fuel efficiency	Eco-driving; platoons; lighter vehicles	Increase
Travel demand (VMT)	Cheaper travel; underserved groups; Shared vehicle model shrinks fleet	Ambiguous
Secondary land use impacts	Sprawl; reduce parking area	Ambiguous

If realized, these climate impacts could affect California climate programs and ARB's responsibilities. For example, ARB and California's Metropolitan Planning Organizations (MPOs) might consider whether travel projections may be affected, potentially impacting GHG reduction targets and investment priorities. Based on current evidence, it is unlikely that AVs will achieve market penetration sufficient to profoundly affect climate programs by 2020. By 2035, the target date for SB 375 emissions reductions, the climate impacts of AVs will be more of a concern, but as of 2014 they remain uncertain. Nonetheless, transportation models and clean vehicle programs should begin to consider these potential impacts.

The main tasks related to AV climate impacts are to monitor developments and adoption timelines. As AVs come to market, any climate benefits should be compared against those derived from other transportation technologies or policies. Meanwhile, ARB should consider the following recommendations:

1. Explore joining the existing interagency Steering Committee on AVs; and look for other means of improving dialogue on AV issues with California regulatory agencies, such as the DMV and Caltrans.
2. Support MPOs and local communities in managing potential AV impacts, starting with incorporating AVs into transportation and land use models.
3. Link developing AV technology to Sustainable Freight Transport Initiative and potential future clean vehicle programs.
4. Promote adoption of AV carshare models that lead to more efficient travel patterns.

Introduction

Automated vehicle (AV) technologies leading to driverless cars have the potential to transform the transportation system in ways that will impact California's climate policy. The California Air Resources Board has requested this report to understand the current state of AVs and their future prospects in order to consider policies that can guide development and adoption in accordance with climate goals. Notably, this report focuses on climate impacts, while ARB must also evaluate any air quality impacts that materialize from AVs.

AV concepts date back to the 1930s, with automakers and researchers pursuing new technologies through the second half of the twentieth century. Rapid development of technology in the last decade, however, has intensified interest in AVs among automakers, academics, regulators and the general public. California has been at the forefront of automated vehicle innovation as the first state to explicitly legalize operation.

Many benefits are ascribed to driverless cars. First and foremost, safety gains could be substantial. Over 90 percent of America's 6 million yearly crashes are attributable to human error and could be vastly reduced in number by automation. Technology also has the potential to mitigate congestion, which imposes high costs on American cities.

Beyond safety and capacity gains, widespread adoption of automated vehicles will affect the energy and climate impacts of the transportation system. Possible climate impacts could eventually include a dramatic increase in vehicle fuel efficiency. Car ownership could be transformed in a world of shared, automated vehicles. On the other hand, congestion reduction may lead to induced demand and increased vehicular travel.

Although there is vigorous discussion around implications of AVs, many of these possible outcomes are uncertain. As carsharing pioneer Robin Chase asked in an April 2014 article for *The Atlantic Cities*, "Will a world of driverless cars be heaven or hell?" In quantitative terms, one researcher notes, "road vehicle automation could plausibly reduce transportation energy demand in the U.S. by 40% - but could also more than double it" (MacKenzie 2014). Ultimately, AV effects will depend not only on technology development, but also on a range of factors including public perceptions, adoption rates and the legal and regulatory frameworks devised. Researchers and policymakers are beginning to grapple with these uncertainties.

This report begins with definitions and a brief overview of AV technology in Section 1. Next, Section 2 provides an outlook for adoption of AV technologies, including regulatory factors and public attitudes. Subsequently, Section 3 analyzes potential energy and climate impacts, drawing on existing studies. Section 4 links these impacts to the relevant climate policies and ARB's transportation responsibilities, including transportation planning efforts and clean vehicle programs. Finally, the report concludes with recommendations and considerations for future study.

1. State of Automated Vehicle Technologies

As of 2014, AVs are developing rapidly. While media coverage has been extensive, much of the research and development naturally occurs outside of the public gaze. Discussion of engineering challenges and solutions is outside the scope of this report. Therefore this section does not aim to serve as a comprehensive technical resource, but instead focuses on definitions and briefly highlights areas of current activity.

What is a driverless car?
A driverless car implies a vehicle without a human driver behind the wheel for steering, acceleration and braking, and so forth. However intermediate degrees of automation are possible and are already in advanced stages of development. It is important to unpack the definition of an automated vehicle because different climate impacts may materialize with different levels of automation.

The National Highway Safety Transportation Administration (NHTSA) has released a five-category framework for classifying AVs.

Exhibit 1: Levels of Automation (Source: NHTSA)

Level 0	Human driver controls all functions.
Level 1	Function-specific automation; e.g. cruise control.
Level 2	Combined function automation; e.g. adaptive cruise control with lane guidance
Level 3	Limited self-driving automation; human driver may need to re-engage.
Level 4	Full automation; no human driver required.

The highest level of automation currently offered commercially is Level 2, which is available to drivers who purchase high-end vehicles such as a Mercedes S-Class with adaptive cruise control and lane assist. BMW and Cadillac offer luxury vehicles with similar capabilities.

Level 3 corresponds to the Google cars and other advanced designs by car manufacturers (Exhibit 2). The Google cars do not conduct trips without a human driver behind the wheel. Current regulation in California actually stipulates the requirement for a driver to be prepared to take control. Early automated driving tests were largely limited to freeways and other controlled conditions, but Google announced in April 2014 that it was engaged in thousands of miles of driving on streets around its headquarters in Mountain View (Google, 2014). These tests demonstrated the ability of the vehicles to navigate suburban streets and respond to other vehicles as well as cyclists and pedestrian movements.

Exhibit 2: Google Driverless Car (Source: Google)

Level 4 vehicles would require no human driver for operation and indeed could operate without any occupants. Networks of shared, taxi-like AVs with intermediate trips by unoccupied vehicles would require AVs of Level 4 capability. As of 2014, no Level 4 vehicles exist. Estimates of when they would be developed range from 2025 to 2050. Possible adoption timelines are discussed further in Section 2.

The Society of Automobile Engineers has proposed an alternative classification, which breaks Level 4 into two further levels. At High Automation, driverless operation is limited to only certain conditions, such as highways or garages, but a human driver may be needed in other instances. At Full Automation, no driver is needed in any circumstance.

Beyond the level of automation, AV technologies may be classified as either autonomous or cooperative. Autonomous AVs rely on sensors and computers onboard the vehicle. The Google car is autonomous when in driverless mode. It processes driving decisions onboard and does not communicate with the infrastructure or with other vehicles.

In contrast, cooperative or connected AVs may have vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications that offer benefits beyond simple automation. In fact, some safety and climate benefits may only be possible with cooperation; for example, research at the UC Berkeley's California PATH (Partners For Advanced Transportation Technology) suggests that without V2V cooperation, smooth braking and acceleration for AVs will not be possible and the same "accordion" effects will occur as in normal traffic.

In comparison with autonomy, cooperation will likely require greater government action to ensure standardization and provide basic infrastructure. A GAO report (2013) notes that broad deployment is required for V2V technologies.

Ongoing Research and Development

Sensors and computing algorithms for vehicle automation are improving rapidly. Google is perceived as a leader. As noted above, its driverless vehicles correspond to NHTSA Level 3 and have driven over 500,000 accident-free miles on California highways and some suburban roads, with limited need for human intervention. Alongside Google, major automakers are conducting automation research. Nissan in particular has publicized Bay Area testing, while Ford and General Motors are leading a partnership to improve vehicle communications. Volvo has prioritized safety advances and announced a plan to test 100 driverless cars in Sweden by 2017 (Geeting 2014).

Beyond the private sector, university- and government-sponsored research is also occurring, in particular focusing on V2I and V2V technologies. In California, Caltrans and UC Berkeley's PATH center have a long-standing cooperation on connected vehicles research, with a test facility in Palo Alto. A US DOT-sponsored V2V Safety Pilot in Michigan ran from 2012 to 2014 with findings expected to be released later in 2014.

Technical challenges remain despite the rapid progress, although engineering confidence in solving them is high. These challenges are briefly discussed in the following section, along with possible barriers to adoption in cost, regulations and customer attitudes.

2. Outlook for Adoption of AV Technologies

Despite the recent progress, numerous barriers remain before adoption of AVs will be widespread. There have been waves of enthusiasm for driverless cars throughout the twentieth century, and while technology progress has accelerated, rapid adoption is by no means guaranteed. Understanding possible adoption patterns is important because they will shape AV impacts on climate.

The barriers to adoption can be grouped into four broad categories.

- Technology improvement: Better mapping, development of the human-machine interface, and more reliable sensors will all be required.
- Cost: AV prototypes such as the Google car are currently costly custom solutions, and cost premiums must fall to stimulate adoption.
- Regulation: Laws to enable continued testing are needed, and further frameworks must address liability, data ownership and other novel AV problems.
- Public acceptance: Public attitudes towards AVs are still in the formative stage, and it is not yet clear whether American drivers desire AVs, to what extent they would trust them on the roads or how much they are willing to pay for AV features.

Technology

Although technology has progressed swiftly in the past decade, there are still problems to be solved before even a Level 3 vehicle could be sold to a consumer for independent operation. Remaining technical challenges (KPMG 2013, RAND 2014) include:

- Improved positioning technology and mapping: Extreme precision is required.
- Weather and terrain sensors: Test vehicles generally operate in optimal conditions, but AVs must be prepared to handle heavy rain, fog, accidents, road work or other unexpected events.
- Failure backups: Vehicles must have robust systems to recognize system failures and respond quickly and reliably.
- Human Machine Interface (HMI): For vehicles that require human intervention and are not fully driverless under all scenarios, there must be a reliable way to notify and engage the human drivers to assume control of the vehicle.

This is only a brief list of remaining challenges, which are extensively covered elsewhere. Most observers appear to agree that technology challenges are addressable, as indeed Google's rapid progress suggests.

Cost

The Level 3 AVs being tested are custom-built, high-cost prototypes. The frequently cited cost of the Lidar remote-sensing system used by the Google car is $70,000. According to RAND (2014), failure to achieve cost reductions has doomed previous automation technologies and could substantially limit future AV adoption. If cost drops too slowly, it will not only be very difficult for manufacturers to achieve economies of scale, but many of the benefits of AVs may be limited as well.

Analysts argue that the cost premium of an automated vehicle would have to drop to $10,000 to become commercially viable for individual consumers. Fagnant and Kockelman (2013) assume a $10,000 premium would correspond to 10 percent market penetration and suggest that even with mass production, such a cost reduction is not likely for at least ten years. Furthermore, a JD Power survey suggested than even a $3,000 premium impacted willingness to purchase an AV. Notably, the high-end Level 2 AV packages sold by luxury car manufacturers cost more than $10,000 over the base price.

However as AV technologies improve, savings in vehicle operations might cover some of the added investment. AVs could become especially attractive for commercial users who are able to absorb the up-front investment. Long-haul trucks and delivery fleets would be attractive for automation, although introduction of AVs into corporate fleets might face difficult labor negotiations.

Regulation

To date, individual states have taken the initiative to regulate AVs while federal action has been slower. The primary focus has been on testing; indeed, the federal government recommends that states only authorize AV operation for testing.

California

California was one of the first states to permit operation of "driverless vehicles" on its roads, enacting California Vehicle Code, Division 16.6 in September 2012. The California law defines AVs for California with the intent of supporting testing and early operation.

SB 1298 directed the DMV to prepare regulations for AV operation by January 2015, with provisions for manufacturer testing and operation. As of Spring 2014, the DMV is engaged in extensive studies and stakeholder discussions related to preparation of two regulatory packages. The first set of rules defined insurance, data collection and training requirements and was released in 2013. The second package will set standards for testing, safety, licensing and vehicle registration and is expected in Fall 2014.

Meanwhile, an SB 1298 Steering Committee has been established, with representation from following agencies:

- California State Transportation Agency
- California Department of Insurance
- California Highway Patrol
- California Office of Traffic Safety
- California Department of Transportation
- California Department of Motor Vehicles
- National Highway Traffic Safety Administration

Notably, ARB is not part of the Committee. If and when climate impacts of AVs become more relevant, ARB may wish to explore joining this group.

Other states
Nevada has been a leader in AV legislation as the first state to explicitly define AVs and requirements for operation, including special certification of compliance. Nevada created a technology certification market to leverage private sector involvement. In addition, the state imposed high insurance requirements for test vehicles and restricted testing to specified geographic areas.

Along with California and Nevada, Florida and Washington, D.C. have also passed AV legislation. As of February 2014, legislative action related to automated vehicles had been introduced or was underway in Arizona, Hawaii, Massachusetts, Michigan, Minnesota, New Hampshire, New Jersey, New York, Oklahoma, Oregon, South Carolina, Texas, Wisconsin and Washington.

Federal actions
The lead federal agency for AV regulation is the Department of Transportation. Within DOT, the National Highway Traffic Safety Administration (NHTSA) is responsible for vehicle safety standards and also helps set research and testing priorities. California agencies such as the DMV and regional MPOs look to NHTSA for guidance.

In February 2014, NHTSA announced it would take steps to support further development of V2V communications technology, with the Secretary of Transportation touting expected safety benefits (NHTSA 2014). Following analysis of data obtained in V2V pilots (described in Section 1, above) NHTSA expects to publish a detailed report and begin drafting regulatory proposals to require V2V devices in future vehicles. Such regulations could serve as a signal to auto manufacturers to accelerate V2V development. Importantly, NHTSA activity is heavily focused on collision prevention as opposed to possible fuel efficiency gains or other environmental benefits.

Beyond NHTSA, other branches of the Department of Transportation coordinate and fund technology and policy research. The Environmental Protection Agency also helps set vehicle weight standards as well as fuel economy standards. As AVs of all levels become more widespread, more federal agencies will likely become involved.

Regulatory needs
A recent RAND Corporation report suggested the guiding principle of supporting and encouraging AVs where they are "better than the average human driver." Defining what this means, however, is a task that remains to be broached. Aside from safety standards, the most significant regulatory tasks concern liability, data security and privacy, among other issues. For example, if an automated system fails, is the manufacturer liable? What if the programmer of the automation system is different from the auto manufacturer? Nonetheless, an April 2014 report by Brookings argued that existing liability law provides an adequate framework for AVs (Villasenor 2014). According to the report, while "the liability concerns raised by vehicle automation are legitimate and important[,]… they can be addressed without delaying consumer access to the many benefits that autonomous vehicles will provide" (Villasenor 2014, 3).

Although many parties are wary of over-regulation, greater federal coordination will likely be required down the line. Volvo's Director of Government Affairs was recently quoted: "In terms of regulatory hurdles, we are very concerned about a state-by-state approach that would lead to a patchwork of state laws" (Geeting 2014).

Consumer Acceptance

Americans are tied to their vehicles and Californians are no different. How willing are Californians to purchase and drive a new technology, particularly one in which they relinquish control? High-profile safety investigations in early 2014 into Toyota and General Motors underline that existing automobile technology systems can fail. Although AVs may be far safer on the whole, drivers will have to trust automated systems in order to hand over control.

Surveys have attempted to get at early consumer attitudes. A February 2014 survey conducted by the Pew Research Center and Smithsonian magazine found that 50 percent of Americans would not ride in a driverless car if it were possible, compared to 48 percent who would (Pew 2014). While this suggests real skepticism, it also implies that Americans are receptive to AVs and could be attracted to them if they perceived benefits.

KPMG (2013) released findings from focus groups held in California, Illinois and New Jersey. Although only a small number of people participated, several interesting findings emerged. Drivers in Los Angeles expressed the greatest enthusiasm for self-driving cars. KPMG also found that nearly a quarter of all social media comments regarding self-driving cars came from California.

Beyond geographic factors, KPMG highlighted that less passionate drivers were most interested in self-driving vehicles. This could be expected, as performance-oriented drivers would not wish to give up control. The finding also reinforces the theory that AVs would significantly reduce the disutility of driving and could therefore increase VMT, as discussed in Section 3 below. In addition, demographic factors also followed expected patterns, as older drivers and female drivers were both more likely to report willingness to use self-driving cars. For older drivers in particular, this could also be related to potential for increased mobility.

Most of the focus group participants indicated that they would not give up their vehicles altogether to participate in a shared vehicle program. Again, this finding should be viewed with caution due to small sample size and early-stage understanding of AVs. Nonetheless, the response suggests that models of a driverless future may take longer to realize than optimists have claimed.

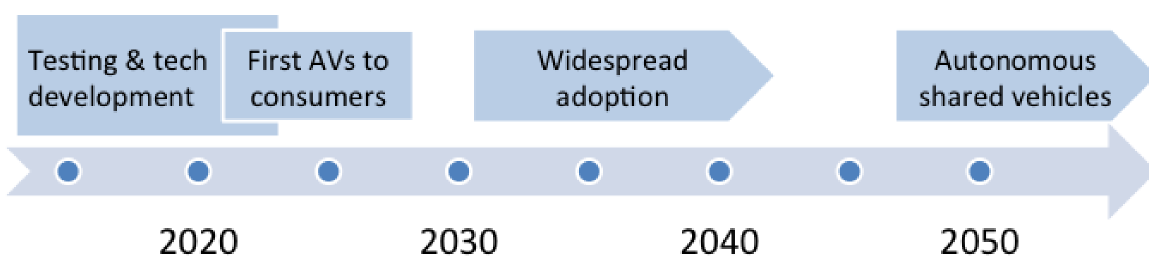
Graduate students at UC Berkeley conducted a small-scale survey of approximately 100 drivers in the Bay Area in 2013 that offers further preliminary indications (Howard and Dai 2013). Survey results showed great interest in possible safety benefits of AVs, but also concern over cost and possible lack of control. The authors included possible environmental benefits among the AV features covered in the survey. They found that respondents valued potential environmental benefits but viewed safety and convenience as much more important.

More work on acceptance and attitudes will occur in the coming years, both in industry and academia. Reliable information will be lacking until Level 4 AV models are available for broader use and until cost premiums fall. From a climate policy perspective, it will be important to track the components of consumer attitudes and whether AVs are seen as a green alternative or a comfort-oriented solution, for example.

In addition, the attitudes of specific subgroups may be more important than those of the public at large. For example, commercial fleets that are able to make upfront capital investments may view AV technologies more favorably and could be leaders in adoption. In fact, mining company Rio Tinto already operates a fleet of automated vehicles in its operations in a remote area of Australia (Validakis 2013). The views of political leaders will also be relevant: whether they are informed as to possible costs and benefits, whether they are influenced by interest groups that perceive threats from AVs or whether they fear backlash from an AV-related incident.

Adoption Timelines
How quickly will California see an appreciable quantity of AVs on its roads? The factors discussed here are inter-related and various scenarios are possible. Some boosters see widespread adoption by 2025; others are more skeptical. While Google executives have been cited as expecting their technology to be available to consumers by 2017, others note the apparent lack of a viable path to market (AP 2014). Furthermore, even the impressive successes of Google's program may take time to translate to non-trained, non-supervised drivers outside of the Bay Area. Exhibit 3 shows a possible timeline for AV adoption synthesized from reports, articles and presentations (including KPMG 2012, RAND 2014, Google, Morgan 2014, Geeting 2014, and others).

Exhibit 3: Potential AV Adoption Timeline



Adoption of alternative fuel vehicles such as hybrids and plug-in electrics can provide an interesting analog. Development of these vehicles dates back to the early 1990s. The first hybrid models, such as the Toyota Prius were introduced in the U.S. in the early 2000s at a significant cost premium and supported by generous tax incentives. Hybrid ownership grew slowly but has accelerated in recent years. By 2013, there were nearly 600,000 hybrids in California, or approximately two percent of California vehicles (Reese 2013). The analogy between hybrids or EVs and AVs should not be over-stressed. However the alternative-fuel vehicle story suggests that it may take at least a decade beyond the first introduction of AVs to consumers to achieve significant market share.

3. Climate and Energy Impacts

AV climate impacts will propagate through changes in vehicle design and vehicle usage. These impacts could result in a major transformation of the transportation network, as many observers and academic studies have proposed. Because of the significant uncertainties, however, reliable modeling of impacts is challenging and there are few studies as of 2014. Exhibit 4 identifies available studies that describe and quantify potential climate impacts.

Exhibit 4: Studies completed to-date quantifying potential environmental impacts of automated vehicles

Authors	Title	Date
Anderson et al. (RAND)	*Autonomous Vehicle Technology: A Guide for Policymakers*	2014
Brown et al.	*An Analysis of Possible Energy Impacts of Automated Vehicles*	2014
Fagnant & Kockelman (Eno Center)	*Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations*	2013
Fagnant & Kockelman	*The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios*	2014
MacKenzie et al.	*A First-order Estimate of Energy Impacts of Automated Vehicles in the United States*	2014
Spieser et al.	*Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore*	2014

The researchers cited here take different approaches. One approach is to simulate a system of autonomous vehicles. Authors set parameters for a model and run a number of iterations. Outputs might include effects on fleet size, VMT, and emissions. Evaluation of a theoretical network of shared autonomous vehicles is often performed using this approach, such as in Fagnant and Kockelman (2014) or in Spieser et al. (2014).

In other studies, a scenario framework is used. Brown et al. (2014) provide estimates for a number of energy and environmental impacts and combine them under different scenarios to provide a range of aggregate energy impacts. Alternatively, in the 2013 Eno report, the authors use a cost-benefit analysis that tallies crash cost savings, congestion benefits and other impacts under low, medium and high market penetration scenarios (Fagnant and Kockelman 2013). In this case, the output is in dollars, not change in fuel demand; fuel efficiency gains are assumed.

Again, it is vital to note that multiple uncertainties must be assessed and therefore many assumptions are necessary. In particular, uncertainties loom over early analysis include:

- Adoption timeline, as discussed in the previous section.
- Market penetration: in the scenarios modeled, how many vehicles are automated and to what level is the automation? What point in the adoption timeline does that correspond to?

- Overlap with other technologies: for example, are the AVs hybrid or electric? What battery technology advances are achieved? Are smart infrastructure technologies implemented?

The following pages classify and synthesize proposed climate impacts from these early studies in order to compare findings and give a sense of directionality and possible magnitudes.

Efficient driving

Human drivers are not only frequently unsafe, they are often inefficient, braking or accelerating too quickly. This in turn burns fuel at a higher rate. Automated braking and acceleration allow more efficient "eco-driving." The impacts are potentially substantial. Relying on studies of eco-driving, Brown et al. (2013) estimate automated braking and acceleration can result in at least a 20 to 30 percent reduction in energy per vehicle mile traveled. Other studies concur, citing fuel economy gains of 23 to 39 percent (Fagnant and Kockelman 2013).

Lighter Vehicles

A large reduction in crash rates will enable car manufacturers to design and produce lighter vehicles. Although these vehicles will be less crash-worthy in the event of a crash, they will be much more fuel-efficient. Studies suggest a possible reduction in vehicle weight of 20 percent, with each 10 percent reduction corresponding to a six to seven percent reduction in fuel consumption (RAND 2014). If crash rates do decrease, regulatory action will be required to allow lighter vehicles on the roads. This would have to occur primarily at the federal level and could present a barrier that pushes realization of this benefit further into the future.

Electrification

If AVs are able to be lighter due to safety gains, they could support adoption of other clean vehicle technologies by freeing up vehicle capacity for improved batteries or hydrogen fuel cells. For example, the battery in a Nissan Leaf weighs 600 pounds (RAND 2014). If crash safety gains allow lighter vehicles and AV driving efficiency gains increase effective battery range, there could be synergies between AVs and EVs. If this dynamic encourages production of affordable alternative fuel vehicles, large climate benefits are possible.

AVs in a sharing paradigm may be even more likely to electrify if they are used within a limited range and able to self-charge. This scenario generates significant media enthusiasm, but appears to be decades away from reality.

Platooning

Fuel efficiency benefits can also be achieved from platooning, the practice of running vehicles together closely with reduced headways in order to cut down on air drag resistance. This would likely require communication between vehicles, although even non-connected vehicles could reduce headways. Platooning would be especially attractive for freight trucking, although light-duty vehicles could platoon as well. In either case, it would be implemented on highways for long-distance travel.

Fuel efficiency benefits from platooning are expected to be on the order of 10 to 20 percent (Brown et al. 2013; Caltrans 2013). The benefits would depend on number of vehicles involved, fraction of the total trip in platoon, and the following distance allowed by the technology. Large-scale platooning might require so-called managed lanes which are specifically set up to handle large "road trains."

Congestion Reduction and Faster Travel

AVs' ability to drive more efficiently will reduce congestion and therefore effectively increase highway capacity without requiring new construction as vehicles drive more smoothly with reduced headways. Adaptive cruise control, if deployed cooperatively in a broad majority of vehicles, could increase effective lane capacity by up to 80 percent (Fagnant and Kockelman 2013, 5). Even a decrease in collisions enabled by AV technology would reduce congestion since up to 25 percent of congestion delays are caused by accidents (RAND 2014, 23). In turn, congestion reduction would reduce emissions directly by cutting down on vehicle idling, while a reduced need for new highway construction would also yield carbon benefits. On the other hand, congestion relief could contribute to additional travel demand, as discussed below.

Benefits in this area can be achieved without full, Level 4 automation and therefore could be expected sooner. However some systems, such as advanced signal control to eliminate intersection delay would require high market penetration and are likely more remote (Fagnant and Kockelman 2013).

Changes in Travel Demand

Travel demand, as measured in vehicle miles traveled, may change in various ways. Most possible effects appear to point towards an increase in travel if AVs increase convenience.

Lower Costs of Travel

Automation that allows the driver to devote his or her attention to other tasks will dramatically lower the cost of travel time as it becomes more productive and enjoyable. This in turn will actually encourage higher travel demand and VMT. Congestion relief could also induce additional travel demand among both AVs and conventional vehicles.

AVs may also directly lower driving costs if insurance premiums drop thanks to safety gains or if fuel economy increases as outlined above. Modeling of travel demand impacts in the recent Eno Center report estimates possible VMT increases of between 2 and 9 percent depending on the level of adoption of AVs in the overall fleet.

Underserved Populations

VMT will also rise if AVs enable increased mobility for elderly, disabled or underage passengers. As the U.S. population ages, this aspect of AVs could become especially attractive. As a high-end bounding estimate, Brown et al. estimate a possible 70 percent increase in VMT per vehicle if all people over age 13 had the same VMT as the highest use demographic.

Shared Ownership and Ridership
Although individuals may drive more in AVs, Level 4 vehicles would enable networks of shared vehicles that can automatically pick people up on demand. Such a model could enable reduced vehicle ownership. This paradigm would create much more efficient patterns of vehicle utilization since, at any given time, only a small percentage of the vehicle fleet is actually in use.

Studies argue for a potentially huge reduction in the total number of vehicles. In a simulation for Singapore, Spieser et al. (2014) found that a shared vehicle model could reduce the vehicle fleet by two-thirds. Fagnant and Kockelman (2014) calculated that a single shared AV could replace 9 to 13 vehicles in an urban scenario.

However, there are significant barriers to a widespread shared vehicle model. New legal structures would be needed, and more importantly, changes in social norms would also be required. In urban centers, shared mobility has been increasing in the United States with services like Zipcar or Lyft and oft-cited statistics indicate that young people are less likely to own a car. Nonetheless, it remains to be seen whether this trend will be sustained and more importantly, how deeply AVs would reduce vehicle ownership.

Land Use Patterns
Depending on the evolution of travel demand and carsharing, secondary effects will be felt in land use. A decrease in the perceived cost of travel could push towards greater sprawl. There are equity implications in this scenario, as wealthier drivers who can afford automated vehicles are able to live further from the urban core but increase the productivity of their commute.

On the other hand, a shared driverless car model accompanied by a reduction in the size of the vehicle fleet could greatly reduce the need for parking. The average vehicle is parked 95 percent of the time and the over-dedication of urban space to parking has been increasingly recognized, for example in the work of Donald Shoup (Shoup 2011). Higher vehicle utilization of shared AVs and the ability to self-park would reduce the need for parking and allow greater urban density. Whether increasing or reducing density, any land use impacts would be realized over longer time horizons.

Transit and Other Modal Shifts
Growth in shared ownership is not the only possible modal implication. Transit could be affected as well. In an extreme case, transit could be replaced by on-demand, driverless taxis, which would increase VMT. Again, this shift would occur years in the future, and labor issues would present a significant obstacle to driverless transit.

Summary of Travel Demand Impacts
Exhibit 5, adapted from the 2014 RAND Corporation report, summarizes various travel effects according to whether they increase or decrease VMT and the likely relevant levels of automation (per NHTSA). On balance, VMT seem likely to increase in the near term following introduction of AVs, but the exact effect will depend on the relevant magnitude of the different influencing factors. As the RAND report (2014, 37) notes, “Even increases in

total VMT can have neutral effects on energy and environmental impacts as long as vehicle efficiencies and/or GHG intensities of fuels are reduced." In addition, development of AV carsharing would counteract the VMT increase, although is only likely to materialize at a later date.

Exhibit 5: Expected effects of Automation on VMT (Adapted from RAND, with author's additions)

Effect	VMT Increase	VMT Decrease	Automation Level
Rebound effect	X		2, 3, 4
Underserved populations	X		4
Car-sharing and reduced vehicle ownership		X	2, 3, 4
Sprawl	X		2, 3, 4
Substitute for transit	X		4

Cumulative Climate Impacts

Findings of potential aggregate impacts related to climate and energy are reviewed in Exhibit 6. Several conclusions jump out. First, there are too few reliable studies covering too wide a range of outcomes to allow drawing comfortable conclusions. Second, comparisons are challenging as the range of modeled output measures vary. Third, researchers are relying on assumptions and estimates mapped onto AVs from other automobile and travel studies. The findings are probably best thought of as bounding or order-of-magnitude estimates at this early stage.

Exhibit 6: Quantified climate impacts

Study	Metric	Effect Magnitude	Time Frame	Notes
Anderson et al. (RAND), 2014	Fuel Economy	+100% - +1000%	2050+	Based on aggressive vehicle weight reductions
Brown et al., 2014	Fuel Demand	-91% - +173%	90% AV penetration	Range based on scenarios with different effects
Fagnant & Kockelman (Eno Center), 2013	VMT	+9%	90% AV penetration	Estimates also given for lower market share; fuel efficiency gains assumed
	Fleet size	-42.6%		
Fagnant & Kockelman, 2014	Energy use	-12%	Fleet is all shared AVs	Per shared AV, vs. avg. light-duty vehicle
	GHG	-5.1%		
Spieser et al., 2014	Fleet Size	-66%	Fleet is all shared AVs	No energy-only outputs modeled

Given the range of predictions cited here, interpretation of the projected magnitudes is difficult. Comparison with other transportation policies is also important. It should be noted that significant gains in fuel efficiency can expected by 2050 even without AV technology (RAND 2014). The energy and climate gains from electrification are more certain and likely greater, while the ability of road pricing and other transportation policies to affect VMT would be more direct than carsharing mechanisms.

Significantly, there is broad consensus around the potential for a rise in VMT for automated vehicles, especially in the earlier phases of AV adoption. Data from users of Level 2 AVs with adaptive cruise control could provide an indication of whether greater perceived comfort actually leads to higher VMT. If broad VMT increases do seem likely, government may have another reason to look to road pricing and other strategiesto manage demand.

Climate impacts must be weighed against other impacts, especially safety. Benefit-cost analysis can provide an approximate analytical framework. In a preliminary attempt, the 2013 Eno report (Fagnant and Kockelman 2013) estimates nationwide annual savings of $37.7 billion, $102.2 billion and $201.4 billion at 10 percent, 50 percent and 90 percent market penetration of AVs, respectively. These are largely realized from safety benefits with millions of crashes potentially eliminated and thousands of lives saved. These estimates are a first approximation only, but the authors argue that they provide an order-of-magnitude valuation.

This section has argued that the overall climate impact on the transportation network will depend in large measure on adoption and whether AVs are shared or individually owned. This points towards a role for policymakers to promote the scenarios that mitigate possible VMT increases. These implications for California climate policy will be discussed in the next section.

4. AVs and Climate Policy in California

As the climate impacts of AVs described in the previous section begin to materialize, California may need to adjust its policies in order to meet its climate goals. ARB will have to respond to these impacts in conjunction with other state agencies, Metropolitan Planning Organizations (MPOs) and local governments.

ARB's mission is to reduce air pollutants. Per AB 32, California's Global Warming Solutions Act of 2006, ARB's legal authority includes reduction of greenhouse gas emissions, including those from cars and light trucks, through 2020. This mandate encompasses transportation-related responsibilities to promote clean vehicles and sustainable regional planning goals that were further developed by SB375 in 2008.

This section aims to highlight policy implications for existing ARB programs and for future statewide climate policies.

Regional Planning

Under SB375, the ARB is directed to set regional greenhouse gas reduction targets. Existing targets call for GHG reductions ranging from 0 to 16 percent by 2035. Metropolitan Planning Organizations are required to develop the plans to meet these targets as part of Sustainable Communities Strategies (SCS). The SCS is required to:

- Identify housing needs and locations to meet them;
- Identify transportation needs and the network to service them;
- Forecast development patterns integrated with the transportation network in order to achieve GHG reductions;
- Quantify the GHG reductions to be achieved.

ARB's role in the process usually focuses on quantification of GHG reductions. AV adoption could potentially affect regions' ability to meet these GHG reduction goals if the impacts outlined in the prior section result in increased travel, without widespread electrification.

Implications for VMT and land use would also affect investments in the transportation network. An investment in a project whose use is expected to extend to 2035 or 2050 may look different if AV effects are incorporated. For example, transit demand may be reduced if driving is a more attractive alternative to users in an AV context. Even if these outcomes remain difficult to model with confidence, planners and funders must begin to grapple with them.

Modeling Challenges

Current transportation and land use models do not reflect possible impacts of automation. Even non-automated carsharing is incorporated in only a limited way. With the advent of AVs, models will need to account for new sources of supply and demand, new utility parameters and new modal preferences.

Academics and transportation modelers have begun to think about these problems. A promising approach is to vary parameters in current models as a bounding exercise, as a

Stanford doctoral student has done in partnership with the Metropolitan Transportation Commission (MTC) for the Bay Area. However, at this point, conjectures about behavioral response remain conjectures. Will the value of time in an AV be closer to that in a current vehicle or in a chauffeured vehicle, or even an office space? It depends on whether drivers can fully concentrate on other activities or are required to remain alert.

As modeling regional AV impacts progresses, it will be necessary to vary not only the attractiveness associated with travel, but also vehicle ownership, cost, adoption timelines, and the other issues discussed in this report. Creating a reasonable range of parameters for each regional transportation system will yield a set of possible transportation, climate and land use impacts, including practical outputs such as road link speed curves and delays in an AV world.

MPO Perspective

MPOs are already beginning to think about AVs. Interviews with San Diego Association of Governments (SANDAG) staff indicate that they are enthusiastic and optimistic about AV adoption. They are currently relying on guidance from the Federal Highway Administration. AV impacts will be incorporated in a discussion of emerging transportation technologies to be presented to the board. In addition, staff is participating in AV workshops sponsored by NHTSA and the Transportation Research Board and engaging in industry outreach.

SANDAG is not yet to the point of incorporating AVs into its transportation demand models, nor does it have a clear path to doing so. Interestingly, SANDAG staff indicated that they are skeptical of an overall VMT increase.

Discussions with MPO staff show that MPOs are facing the same uncertainties described at length in earlier sections. Specific questions raised include:

- What will be the market penetration of AVs?
- How should each region weigh adoption scenarios?
- Should the MPO play a role in shaping regulation to shared automated vehicles?

Many of these questions can only be answered as AVs accumulate more miles on the roads. Although the primary resources are being provided by agencies like NHTSA, conversatiosn with MPO staff indicated a possible role for ARB. First, MPOs are discussing regional plan implications and sharing AV information amongst themselves in an informal way. ARB could play a clearer coordinating role in this area. Second, the ARB could provide information and support to MPOs on the climate implications of AVs. As a body of reliable studies becomes available, ARB can synthesize the findings, building on the model of this report. A series of clearly categorized, concise references could offer guidance and help MPOs set priorities. In this vein, MPOs note that a broader ARB study of AV climate impacts, where relevant, could be a useful resource. However for such a study to offer useful information, more data would need to be available once AVs reach consumers and their behavior can be observed.

Vehicle Policies

Clean Cars Program

The ARB manages California's Advanced Clean Cars Program, which coordinates policies to control particulate emissions as well as greenhouse gases. The Program covers cars and light duty trucks and consists of standards and incentives. Regulation requires reduction of smog-forming emissions and greenhouse gases by 2025 through improved fuel efficiency and emissions standards. At the same time, the introduction of the Zero Emissions Vehicle Program incentivizes sale of the cleanest cars available including battery electric, fuel cell and plug-in hybrid electric vehicles. The goals of the Program will be unaffected by AV development in the near-term since there is unlikely to be widespread availability of AVs during the scope of the program, and their climate impacts remain to be proven.

Freight Transportation

Freight emissions are responsible for 10 percent of all statewide GHG. As discussed in Section 3, AV technologies could have particular applications for increasing fuel efficiency in freight, such as truck platooning. The ARB is currently developing the Sustainable Freight Transport Initiative (SFTI), a long-term strategy to move freight more cleanly and efficiently, in part through mode shifts and encouragement of alternative fuels. SFTI is at an early stage of stakeholder engagement, including assessment of clean freight technologies. Examples of trucking technologies identified for assessment include advanced combustion, powertrain improvements, alternative fuels, and aerodynamics. ARB has proposed directing cap-and-trade funding to advanced technology freight demonstrations (although as of this report, the Governor's budget does not include allocation of these funds). As AVs are tested and implemented, they should be part of the suite of technologies evaluated as part of the SFTI process.

AVs and Future California Climate Regulation

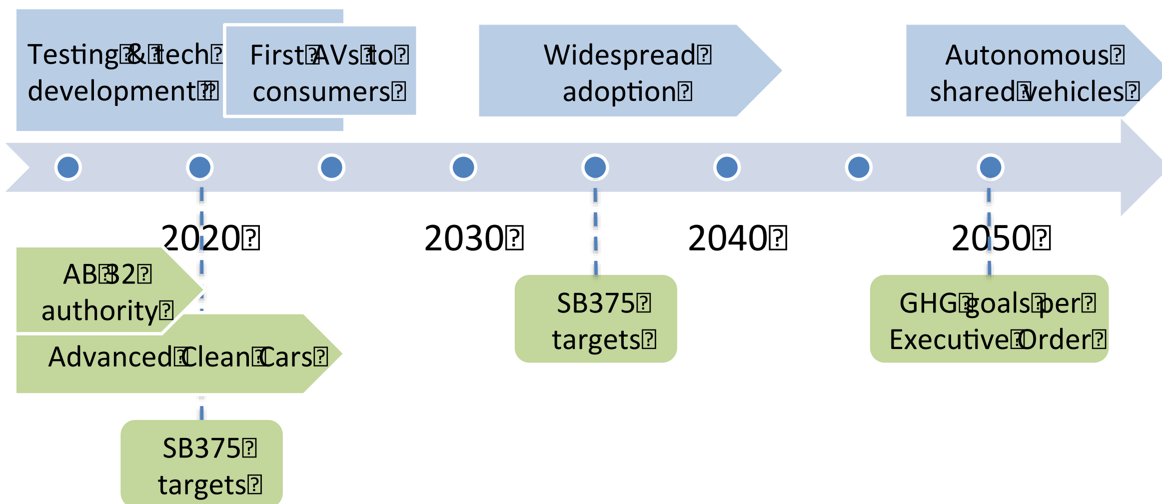
ARB's current AB 32 authority may expire in 2020, although it may be extended through proposed legislation. As of 2014, ARB updated its Scoping Plan to "maintain and continue economic sector-specific [GHG] reductions beyond 2020…" In the Scoping Plan Update, transportation is identified as one of the nine key focus areas. The document explicitly notes, "Early studies show that vehicle automation could enable dramatic emissions decreases, or emissions increases, depending on the level of increased vehicle and systems efficiency they enable, how the vehicles integrate with an alternative fuels infrastructure, and the degree to which they may induce additional vehicle travel" (ARB 2014). The Transportation Working Paper Appendix briefly mentions "transportation connectivity among vehicles and between vehicles and infrastructure" and advises "exploring potential benefits of new mobility innovations of connected and autonomous cars" (ARB 2014).

Opportunities to promote AV benefits, if they exist, are closely linked to possible synergies between AVs and EVs. If future clean vehicle programs are created, incentives could be implemented to encourage these synergies so that AVs are more likely to be electric, mitigating the climate impacts of VMT increases. The Governor's 2013 Zero-emissions Vehicle (ZEV) Action Plan provides an example for promoting emerging sustainable vehicle technologies.

Additional incentives could be appropriate in the freight sector to enable smoother driving or platooning. These might be incorporated in the SFTI or in future programs. Again, the key task is to evaluate the efficiency and emissions reduction benefits of these technologies in comparison with others. This cannot reliably occur until they are closer to deployment.

Exhibit 7 reproduces the adoption timeline from Section 2, with the addition of climate policy milestones.

Exhibit 7: AV Adoption and California Climate Policy



This timeline reinforces the idea that AV tasks for ARB are oriented towards monitoring and research, although climate policymakers can begin to reflect on what form climate-related AV incentives might take if and when they become appropriate. Recommendations along these lines are outlined in the next and final section, along with considerations for future discussion.

5. Outlook and Recommendations

Although AVs are developing at a faster pace than ever before and receiving enthusiastic media coverage, many of the impacts discussed are still years away. Regulation may be required; but to the degree that AVs have the potential to yield social benefits, premature regulation could be harmful. ARB and other state agencies should monitor AV development, as well as support future research, to help guide their actions.

ARB's specific role fits within the larger context of state policies towards AVs. It is possible that social benefits in safety and congestion reduction could justify pro-AV policies even if climate impacts were negative. However, there are multiple paths for AVs to take in their evolution, and some will be more climate-friendly than others. The ARB should focus on promoting those paths for AVs.

In light of these considerations, ARB may consider the following courses of action:

1. Explore joining the interagency Steering Committee on AVs; and look for other means of improving dialogue on AV issues with California regulatory agencies, such as the DMV and Caltrans.
2. Support MPOs and local communities in managing potential AV impacts, starting with incorporating AVs into transportation and land use models.
3. Include evaluation of AV technologies as part of Sustainable Freight Transport Initiative and potential future clean vehicle programs.
4. Promote adoption of AV carshare models.

1. Participate more actively in statewide AV policy
As noted in Section 2, California already has an interagency Steering Committee for AVs that does not include ARB. ARB may want to explore joining this group to take a more active role in AV policies, especially as the scope of potential climate impacts becomes clearer. In addition, efforts should be made to develop ongoing dialogue and cooperation between agencies. In order to promote this cooperation, responsibility for monitoring AVs, perhaps in the form an AV liaison, could be formally added to an ARB staff duties. Further, current efforts to coordinate state agency-funding transportation research can easily be expanded to include research on AV technology.

2. Support MPOs in modeling and managing AV impacts
As AVs come closer to market, ARB should provide support to help MPOs evaluate the effectiveness of strategies aimed at maximizing climate benefits from this technology. This could begin with offering more resources and technical support to MPOs and local communities to support incorporating AV impacts into transportation and land use models. In addition, although several mechanisms already exist for local and regional authorities to share information, there may be a need for a venue to bring together state, regional and local governments, industry partners, academics, and other stakeholders to advance understanding of the technology and its uptake.

3. Link AVs to Clean Vehicle Programs

Some aspects of AV technology, such as smoother driving or truck platooning, promise to have positive impacts for climate and energy. As these technologies become available on the market, ARB could link them to its broader promotion of clean vehicles. For the light duty sector, this would likely not take form as part of the current Clean Cars Program, given the extended AV adoption timelines discussed in this report. For freight vehicles that may be early adopters, automation technologies could be promoted once the technologies are more advanced and reliable estimates of environmental and other impacts are established.

4. Promote Adoption of AV Carshare Models

If climate benefits of AVs are likely to be realized, it may be in the context of shared vehicles, where the vehicle fleet shrinks and there are fewer single-occupancy trips , mitigating the convenience benefits of AVs that push towards greater travel. Therefore, as AVs become available to consumers, ARB may look for policies to promote carshare models for them. This might include:

- Supporting further research as data become available;
- Drafting a policy statement to enumerate benefits of AV carsharing;
- Identifying legal or legislative barriers;
- Creating an incentive program to promote supply of carsharing AVs as well as participation;
- Use of cap and trade funding to support realization of AV climate benefits.

These actions may be years away. However an awareness of options could help to guide research, organizational priorities and discussions with external groups, whether they are legislators, auto industry groups, or the public.

Conclusions and Further Questions

There appears to be no immediate direct regulatory role for ARB governing AV development. It is however important that state agencies closely monitor AV evolution to verify climate impacts as the vehicles are adopted by the state's drivers.

In their evaluation of AVs, ARB and other relevant California agencies should also adopt realistic, medium-term outlooks. Even as technology challenges are rapidly solved, cost or perception barriers may slow widespread adoption of the most advanced technologies. Even if adoption is rapid, AVs should be evaluated against other policies that may hold greater promise in achieving climate goals.

This report aims to serve as a foundational resource, but further AV questions will inevitably arise. As more information becomes available, ARB may consider more focused discussions to guide its stance towards AVs. Issues to consider may include:

- What are pressing data needs for more reliable climate impact estimations?
- What level of emerging data would trigger a consideration of regulatory action?
- What kinds of cooperation with researchers or industry groups would be most productive and yield the most information?

ARB may also consider development of a more robust list of key AV uncertainties related to its programs and priorities in order to guide monitoring of AV issues in the coming years.

Projections of the timing and adoption of automated vehicles remain fluid, but there is a broad consensus that AVs are coming. Technological possibilities alone will not drive outcomes; evolving regulations and attitudes will be just as influential if not more so. California's policies will play a role in guiding AV evolution to maximize the social benefits and minimize the climate costs.

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