Center for American Progress

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The Impact of Vehicle Automation on Carbon Emissions

Where Uncertainty Lies

By Myriam Alexander-Kearns, Miranda Peterson, and Alison Cassady

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Introduction and summary

When one thinks of autonomous vehicles, or AVs, it is difficult not to imagine the world of tomorrow. It is easy to visualize safely cruising down the highway while reading for pleasure or writing a work email—rather than watching the road. Vehicle automation promises to transform how people get to work, run errands, and generally travel through the nation's streets and highway systems. Children could commute to school alone, without relying on a parent. One can also imagine a sight-impaired person traveling alone to a doctor's appointment. In cities, someone could hail an autonomous vehicle with a ride-sharing app and ride with other passengers going a similar direction. The idea of driverless robot cars has captured the public's imagination as automakers and technology companies promote the potential leisure, safety, and environmental benefits of AVs.

Today, automakers are already adding features to new vehicle models that assist drivers, such as parking assistance, lane centering, and automatic braking. As these features become standard in cars, automakers have set their sights on creating autonomous vehicles that do not need drivers at all. Silicon Valley and ride- and car-sharing companies are investing in technology and betting on the transportation sector's shift toward autonomous vehicles.

In the midst of these advances in vehicle technology, the international community is working to address one of the greatest challenges of our time: climate change. The United States has committed to reducing its greenhouse gas emissions 26 percent to 28 percent below 2005 levels by 2025 and to achieving greater emissions reductions in the future.[1] To meet that goal, the United States will need to cut emissions from the transportation sector, which accounted for 26 percent of the country's greenhouse gas emissions in 2014. Of these transportation sector emissions, 61 percent came from light-duty vehicles, such as passenger cars.[2]

Autonomous vehicles—particularly those that are passenger cars—could significantly affect the country's ability to cut greenhouse gas emissions and move toward a carbon-free economy. Existing studies suggest that three main factors will determine whether putting more AVs on the road increases or decreases tailpipe carbon emissions: effect on the total vehicle-miles traveled in the United States; impacts on congestion; and AVs' fuel efficiency and fossil fuel consumption. As such, autonomous vehicles must be assessed not only for their safety but also for their effect on carbon emissions levels.

To that end, the Center for American Progress reviewed the existing literature on the environmental impacts of automation in the light-duty vehicle sector. We found that existing research does not draw clear and consistent conclusions about the impact of autonomous vehicles on the environment generally and climate specifically. In particular, the research reviewed shows that:

- **Vehicle miles traveled, or VMT—the aggregate number of miles driven by vehicles in a given year—could increase because automation lowers the opportunity cost of driving.** This could encourage people to take more car trips or accept longer commutes, since drivers would be able to multitask in vehicles rather than focusing on the road. Additionally, autonomous vehicle technology could allow groups of people currently unable to drive—such as the elderly, young, and people with disabilities—to travel alone in autonomous vehicles, putting more people on the road.

- **VMT could decrease if autonomous vehicle technology is paired with ride- and car-sharing services.** A system of shared autonomous vehicles could discourage individual car ownership and use technology to plan efficient routes to transport people from point to point. At the same time, however, shared autonomous vehicles could increase overall VMT if they make frequent passengerless trips to pick up their next client. Specialized software programs could mitigate this effect by planning the most efficient routes.

- **Automation could reduce congestion and make each mile traveled more efficient.** Autonomous vehicles that communicate with each other and their surroundings may drive more smoothly, without needing to frequently brake and accelerate. Fully autonomous and connected vehicles could reduce the number of traffic accidents and, therefore, unnecessary idling on roads.

- **Drivers may not realize the congestion benefits of automation for years, until a large share of vehicles on the road are equipped with autonomous technology.** In the shorter term, VMT and congestion could worsen as autonomous vehicles join the fleet without displacing traditional vehicles.

Automakers and boosters of autonomous vehicle technology argue that autonomous vehicles have the potential to transform the U.S. transportation sector and make it more efficient. To manage this transformation, however, policymakers need more definitive research on how deployment of autonomous vehicles could affect the environment in the short- and long-term.

In 2016, emissions from the transportation sector surpassed those from power plants.[3] The private sector and policymakers should conduct deeper research into the emissions impact of autonomous vehicles before committing the United States to a transportation path that could lock the country into more VMT and higher levels of carbon pollution. CAP recommends several potential avenues for additional research, including the effects of automation on travel patterns and VMT; alternative fueling; driver behavior and value of driving time; traffic data collection and sharing; and the role of electric drivetrains in autonomous vehicles.

While many effects of autonomous vehicle deployment remain to be seen, researchers do know for certain that emissions can be minimized by electrifying light-duty cars. As autonomous vehicles become more common on the nation's roads, the logical way to guarantee a positive environmental impact is to combine autonomous technology with electrification.

What are autonomous vehicles?

As established by the National Highway Traffic Safety Administration, or NHSTA, there are five levels of automation starting at level 0, or no automation.[4] (see Table 1) Level 0 vehicles may have passive sensors that detect external objects and provide warnings to drivers but nothing more.[5] Level 1, or function-specific automation, assists drivers in controlling specific vehicle functions, such as adaptive cruise control, electronic stability control, lane centering, and automatic braking.[6] Level 2, also known as combined-function automation, automates two or more individual vehicle control functions to work together in place of driver specific commands.[7] Examples of level 2 automation include adaptive cruise control functioning simultaneously with lane centering.[8] Level 3, or limited self-driving automation, allows the driver to be relieved of driving the car while remaining ready to retake control.[9] At the top of the spectrum is level 4, full self-driving automation, which allows the car to function completely without a driver. While levels 1 through 3 all require some level of human driver participation and control, level 4 represents the only true driverless car and may or may not have basics such as steering wheels.[10]

SAE International, formerly the Society of Automotive Engineers, has established a similar framework for levels of automation, with one main difference: the SAE system separates NHSTA's level 4 into two levels—level 4 and level 5. A level 4 vehicle can drive completely on its own under some driving conditions, such as within a specific geographic area. A level 5 vehicle can drive on its own in any driving conditions.[11]

In the 1980s, the BMW Group released its first model with electronic stability control, or ESC. ESC uses sensors and an automatic braking system to bring the car back in line when stability wavers. While it appears under other names, such as interactive vehicle dynamics in Ford Motor Co. vehicles, many manufacturers have been employing this level 1 technology in vehicles since the 1990s. It is now standard on most recent models.[12]

TABLE 1

Automated vehicles on American roads today and in the future

Examples of automated vehicle standards set by the National Highway Traffic Safety Administration

Level	Name	Example of automation
Level 0	No automation	Manual control of all functions
Level 1	Function-specific automation	Pre-charged automatic braking
Level 2	Combined-function automation	Blind spot monitor and intuitive parking assist
Level 3	Limited self-driving automation	Pilot driving system feature with human present
Level 4	Full self-driving automation	Vehicle can drive everywhere without human at wheel

Sources: National Highway Traffic Safety Administration, "Preliminary Statement of Policy Concerning Automated Vehicles" (2013), available at http://www.autoalliance.org/index.cfm?objectid=CC9678B0-A415-11E5-997E000C296BA163; Will Oremus, "Is Autopilot a Bad Idea?" Slate, July 6, 2016, available at http://www.slate.com/articles/technology/future_tense/2016/07/is_tesla_s_style_of_autopilot_a_bad_idea_volvo_google_and_others_think_so.html; Audi USA, "Audi sees human control as important element in self-driving systems," Press release, July 18, 2016, available at https://www.audiusa.com/newsroom/blog/company-articles/2016/07/audi-takes-incremental-approach-to-introducing-piloted-driving.

Vehicles with automation technology in levels 1 through 4 use sensors to receive information from their environment that helps the vehicle safely carry out tasks. Additionally, some vehicles have the ability to communicate with their surroundings, known as vehicle-to-infrastructure, or V2I; vehicle-to-vehicle, or V2V; and even vehicle-to-pedestrian, or V2P, technology. Collectively, these three categories are known as vehicle-to-everything, or V2X, technology, or generally as vehicle connectivity.

Vehicle connectivity technology allows a vehicle to perform driving functions while staying aware of lane divisions, medians, and pedestrians and bicyclists. It also communicates information to the vehicle and other vehicles on the road about red lights, traffic jams, and unexpected impediments such as ice, approaching bad weather, animals, or even a child running into the street. Examples of vehicle connectivity technology available today include General Motors Co.'s OnStar system and Ford's Sync system. Elon Musk, founder of Tesla, predicts that at its most advanced, vehicle connectivity will allow a level 4 driverless car to navigate to pick up a rider who summons it from the other side of the country.[13]

Automakers and tech companies push forward with AV development

Automation and vehicle connectivity technology represent the largest transportation sector disruption in decades. To that end, automakers are racing to create vehicles with the advanced automation and connectivity technology needed to stake a claim in the emerging driverless car market.

Automaker investment in autonomous vehicles

Automakers are investing billions of dollars in the development and deployment of automated vehicle technologies. Most companies are already including automated features in new models. For example, Honda Motor Co. has included its Sensing suite of level 2 automated features in even its most affordable cars, such as the Civic.[14] Similarly, the Volvo Group introduced its own level 2 package of features called Pilot Assist with the release of its 2017 models.[15] Nissan introduced its level 2 ProPilot system in models in 2016 and plans to introduce a collection of 10 models with near-full autonomy, or level 3, by 2020.[16]

Several car companies are moving quickly toward full automation. As shown in Table 2, numerous automakers have announced plans to introduce level 4 AVs within the next 15 years. By 2025, Ford plans to make AVs available for personal ownership.[17] BMW plans to have a full level 4 AV on the road in the next five years.[18]

Partnerships with ride-sharing companies

Ride-sharing companies Uber and Lyft are teaming up with automakers to build fleets of driverless cars, which they see as becoming ubiquitous in cities.[19] By deploying self-driving cars, ride-sharing companies can become more efficient and profitable. AVs allow ride-sharing companies the opportunity to mechanize their service and eliminate the need to pay human drivers—an issue that labor organizations have already noticed.[20]

General Motors has established a $500 million partnership with Lyft, and Volvo is partnering with Uber to design a level 4 AV by the end of 2021.[21] Ford has committed to building a fleet of level 4 AVs by 2021 for an as-yet-to-be-named ride-sharing company. In September 2016, Uber launched a small pilot fleet of nearly self-driving Ford Fusions for its ride-sharing service in Pittsburgh.[22] Uber plans to expand its pilot fleet to 30 vehicles by the end of 2016 and triple the test fleet in 2017.[23]

TABLE 2

Expected level 4 autonomous vehicle market rollouts

Automakers are racing to bring autonomous vehicles to the roads

Company	Anticipated release date
Tesla	2018
Honda	2020
Nissan	2020
Toyota Motor Corp.	2020
Volvo	2020
BMW	2021
General Motors Co.	2025
Ford Motor Co.	2025
Audi	Late 2020s
Daimler AG	2020 to 2030
Kia Motors	2030

Note: Tesla's 2018 rollout date may be for a prototype, which would not be available to consumers.

Sources: Driverless car market watch, "Forecasts," available at http://www.driverless-future.com/?page_id=384 (last accessed October 2016); Nick Jaynes, "Here's the timeline for driverless cars and the tech that will drive them," Mashable, August 26, 2016, available at http://mashable.com/2016/08/26/autonomous-car-timeline-and-tech/#cLqSg2ji0sqB; Keith Naughton, "Ford to Sell Driverless Cars to Public by 2025, CEO Says," Bloomberg, September 12, 2016, available at http://www.bloomberg.com/news/articles/2016-09-12/ford-to-sell-driverless-cars-to-consumers-around-2025-ceo-says; Mike Ramsey, "Nissan Speeds Ahead of Rivals with Plans for Driverless Car," The Wall Street Journal, October 29, 2015, available at http://www.wsj.com/articles/nissan-speeds-ahead-of-rivals-with-plans-for-autonomous-car-1446121737; Alexandria Sage, "Honda shows off self-driving cars at new Calif testing facility," Reuters, June 2, 2016, available at http://www.reuters.com/article/us-honda-self-driving-idUSKCN0YO09S; Yoko Kubota, "Behind Toyota's Late Shift Into Self-Driving Cars," The Wall Street Journal, January 12, 2016, available at http://www.wsj.com/articles/behind-toyotas-late-shift-into-self-driving-cars-1452649436; Keith Naughton, "Can Detroit Beat Google to the Self-Driving Car?" Bloomberg, October 29, 2015, available at http://www.bloomberg.com/features/2015-gm-super-cruise-driverless-car/; Lauren Abdel-Razzaq, "Self-driving car technology moves to forefront at NAIAS," The Detroit News, January 16, 2015, available at http://www.detroitnews.com/story/business/autos/detroit-auto-show/2015/01/13/self-driving-car-technology-naias/21731773/.

Technology companies' investment in autonomous vehicles

The competition to put the first driverless cars on the road is not just among traditional automakers. Tech giants such as Google and Apple are also getting involved. Given that AVs will rely so heavily on technology—and also provide passengers with added work or leisure time—it is no surprise that tech companies would see AVs as an open market for their products.

Apple has released very little information to the public about its Project Titan, but media reports have suggested that Apple plans to release a level 4 electric vehicle that fully integrates with the Apple operating system and range of products in the next decade.[24] Google has been more public in the marketing of its various AV pilots, including a new vehicle prototype and modified vehicle that have completed more than 2 million miles of test-driving on public roads in four states.[25]

Additionally, automakers are teaming up with technology companies to speed their transitions to automation. Lexus has collaborated with Google to use its automation system in Lexus SUVs, including a Lexus RX 450h AV pilot.[26] In 2015, Audi AG partnered with Delphi, a Google competitor, to pilot an Audi SQ5 modified with a Delphi Drive automation system.[27] Google is also working to provide the technology and mapping infrastructure for widespread ride-share use, which it believes will ramp up after 2020.[28]

Automakers are investing heavily in order to catch up on developing proprietary technology.[29] In 2015, for example, Toyota Motor Corp. announced a $1 billion commitment over a period of 5 years for developing artificial intelligence and robotics for use in its vehicles.[30]

The Obama administration responds to AV development

In 2016, federal regulators worked to catch up with the rapid pace of technological development. With an entirely new kind of automobile soon to appear on roads, autonomous vehicle deployment presents a high level of both risk and reward for public safety. Without proper regulation, potentially faulty AV technology could present a major public safety hazard on roadways and to pedestrians. Carmakers and technology companies also promise that vehicle connectivity and AV technology would improve public safety. On average, almost 33,000 Americans die in motor vehicle accidents each year.[31] According to U.S. Department of Transportation, or DOT, research, vehicle connectivity could help car crash rates drop up to 80 percent, presenting policymakers with a major opportunity to make driving safer.[32]

The potential risks and rewards of AV technology have attracted high-level attention in Washington. At the North American International Auto Show in Detroit in January 2016, Secretary of Transportation Anthony Foxx described a "bold proposal" to "do everything we can to advance safe, smart and sustainable transportation innovations like vehicle automation."[33] Secretary Foxx also announced a proposed $4 billion investment over a period of 10 years to help pave the way for AV development, although Congress has not approved a final budget allocating these funds.[34]

The DOT also created the Smart City Challenge, a $50 million competition in which medium-sized cities, such as Pittsburgh and Denver, submitted plans to design innovative transportation systems for their cities. The DOT asked applicants to consider how automation technology, vehicle connectivity technology, and big data could "reduce congestion, keep travelers safe, protect the environment, respond to climate change, connect underserved communities, and support economic vitality."[35]

In June 2016, the DOT announced Columbus, Ohio, as the winner over four other finalists.[36] The city will receive $40 million from the DOT, on top of $100 million in other funding, to create corridors specifically for AVs and to equip buses, taxis, and other cars with vehicle-to-vehicle communication.

Electrification is also a large part of Columbus' efforts to expand personal mobility for its residents: The city plans to convert its city vehicle fleet to electric vehicles, or EVs, and use electric shuttles to link bus services.[37]

In September 2016, the DOT and NHTSA released the Federal Automated Vehicles Policy, which lays out a path for the introduction and deployment of what the DOT calls "highly automated vehicles," or HAVs.[38] Specifically addressing level 3 and 4 vehicles, the Federal Automated Vehicles Policy offers guidance on vehicle performance and safety testing and provides a framework for consistent state policies. It also discusses NHTSA's authority to offer additional safety guidance and identifies new tools and regulatory structures that automakers and tech companies can use to put HAVs on the road.[39] In addition, the department expects to release a proposed rule by the end of 2016 requiring carmakers to include vehicle connectivity technology in all new light-duty vehicles over a number of years.[40] Basic vehicle-to-vehicle connectivity will help vehicles with all levels of automation communicate with one another to reduce the number of crashes and traffic jams.

In October 2016, the DOT announced plans to create an Advisory Committee on Automation in Transportation to support the department's efforts in framing federal policy in this area.[41] Specifically, the new committee will "assess the Department's current research, policy and regulatory support to advance the safe and effective use of autonomous vehicles" and present recommendations to the secretary of transportation.[42]

Regulators from the U.S. Environmental Protection Agency, or EPA, have started studying the potential effects of AV technology on greenhouse gas emissions. In the past year, agency officials have met with auto industry representatives, academics, and environmental groups to collect information on this topic. Christopher Grundler, head of the EPA's Office of Transportation and Air Quality, said that the agency has "learned enough to know the future of [connected and autonomous vehicles] could be utopia or dystopia for the environment."[43]

Key research on environmental impacts of autonomous vehicles

The United States has committed to significant carbon emissions reductions in order to avert the worst impacts of climate change. In light of these commitments, it is critical to examine the development of automation technology and self-driving vehicles through the lens of climate change. On its own, autonomous vehicle technology will not affect carbon emissions from light-duty vehicles; however, the application of the technology will herald changes in how Americans, particularly in urban areas, travel from one place to another. A transformational change in the transportation system could have significant implications for the climate.

Whether AVs mitigate or worsen carbon pollution from light-duty vehicles in the transportation sector will depend on three key factors: their effect on the total vehicle-miles traveled in the United States; their impacts on congestion; and their fuel efficiency and fossil fuel consumption.

A transformational change in the transportation system could have significant implications for the climate.

Research on these factors, however, has so far been limited and inconclusive. A 2014 study by the National Renewable Energy Laboratory particularly highlights examples of the uncertainties in existing research. The study found both potential positive and negative energy outcomes of increased AV use across all automation technology levels. Among the positive impacts are enabling electrification of vehicles and making vehicles more lightweight. However, these impacts are balanced by increased travel demand and increased travel among underserved communities such as the disabled and elderly. The study concludes that significant uncertainties regarding energy impacts remain and warrant continued research, including using data collection from demonstration programs.[44]

In the sections that follow, the authors highlight significant studies that have examined these and other factors and identify areas of future research to fill in the gaps. The studies that this report focuses on examine how automation will affect light-duty vehicles; it does not cover research on heavy-duty vehicles, freight, aviation, and trucks.

Vehicle-miles traveled

Vehicle-miles traveled is a common measure of the aggregate number of miles driven by vehicles in a given year. An increase in VMT generally leads to an increase in tailpipe emissions unless otherwise offset by improvements in vehicle efficiency and pollution control. Consequently, whether automation leads to greater travel demand or reduces VMT will help determine the climate impact of AV deployment. So far, researchers have drawn contradictory or uncertain conclusions about the aggregate effects of automation on VMT.

The RAND Corporation conducted a literature review of existing studies and concluded, "AVs appear likely to reduce many of the costs typically associated with automotive travel, which [is] likely to stimulate growth in VMT."[45] Essentially, automation could reduce the opportunity cost of driving—or the potential loss a driver might experience by choosing to drive over other activities, given limited time in a day. In an AV, an individual can engage in other activities—such as checking email or reading—while the car maneuvers itself and therefore does not have to give up that time. As a result, people may choose to live farther away from their workplaces or take vehicle trips they otherwise would have avoided due to the opportunity cost.[46]

Automation could put entirely new classes of drivers on the road.

In addition, automation could put entirely new classes of drivers on the road. In 2013, the Eno Center for Transportation examined the impacts of deploying fully autonomous vehicles and vehicles equipped with vehicle-to-everything technology. One important gap in this research is the quantification of impacts. In its analysis, Eno did not attempt to quantify or assign monetary value to the predicted impacts. The magnitude of the effects on the environment would depend on how much additional VMT is induced. Eno concluded that travel demand could increase with automation, as AVs could facilitate personal mobility for those who cannot drive on their own—the elderly, the young, and people with disabilities.[47] Sarah Hunter, the policy director for X, the technology innovation component of Google, has acknowledged this challenge: "What we're going to have is people who are locked at home able to get around for the first time. That's a great outcome from an equity perspective. From a number-of-cars-on-the-road perspective, not so great."[48]

Some experts see ride-sharing—when at least two passengers ride together in a vehicle—and car-sharing—when drivers pay a fee to use a car for a set time—as a potential antidote to rising VMT from automation. Essentially, the number of eligible drivers may increase, but the way Americans transport themselves will change as well. Individual car ownership will likely give way to on-demand ride-sharing and car-sharing powered by AV technology.[49]

The Massachusetts Institute of Technology's Senseable City Laboratory has conducted research on AVs in urban settings. They concluded that fully autonomous vehicles incorporated into ride- and car-sharing programs—known as shared autonomous vehicles—could reduce the number of vehicles on the road 80 percent while still getting every passenger to where they need to be, when they need to be there.[50] The Eno Center for Transportation further suggested that shared AVs would not have to drive around looking for parking, as city drivers of conventional vehicles often do, thereby cutting VMT.[51]

The University of Texas at Austin partnered with the University of Utah to study the potential benefits of shared autonomous vehicles, even at low levels of market penetration. The researchers simulated a fleet of shared autonomous vehicles operating in Austin, Texas, that combined on-demand services such as UberPool with full automation. They also created algorithms to ensure efficient pickups and drop-offs. Under these circumstances, one shared autonomous vehicle replaced 9.3 regular vehicles, assuming that one person drove each regular vehicle alone and made three trips each day.[52]

Some experts see ride-sharing and car-sharing as a potential antidote to rising VMT from automation.

It remains unclear whether transitioning to a shared autonomous light-vehicle transportation system would fully offset any increase in VMT from adding new drivers and demand. While the number of vehicles on the road could decline, overall distance traveled by the autonomous vehicles on the road could increase. The UT Austin and University of Utah analysis above found that as shared AVs "move in order to better serve current unserved and future anticipated demand," VMT can increase.[53] Initial modeling in a small market share shows dramatic increases in VMT. The researchers' simulation produced an 8 percent increase in VMT when shared AVs represented just 1.3 percent of car trips.[54]

With a small number of shared AVs on the road, each would have to drive a certain distance to reach its next customer, and many of these trips would be "deadheading," or making a trip without a passenger.[55] With greater market penetration, and in a denser urban setting, shared AVs would have to drive fewer miles to reach their next customers, as there would likely be more cars close by to each customer. Research by David Levinson predicts an initial VMT increase from deadheading, although he suggests that a shared AV system and logistical planning can minimize the passengerless miles.[56] As Levinson discusses, the portion of AVs that will be privately owned versus shared is uncertain and will affect overall travel demand.[57]

Google's testing of its AV prototype demonstrates the potential endurance of a car with no driver that is constantly on the road. In January 2016, Google reported that each of its self-driving test vehicles was driving, on average, 10,000 autonomous miles to 15,000 autonomous miles per week on public streets. Since 2009, the cars had cumulatively driven nearly 1 million miles in manual mode and more than 1.4 million miles in autonomous mode.[58] In contrast, as of July 2016, the average U.S. driver drives 13,476 miles annually.[59]

Congestion

Related to the issue of travel demand and VMT is traffic congestion. A car driving through heavy traffic uses more fuel and emits more pollutants than a car moving smoothly through an uncongested area over the same distance. Congestion, therefore, is more than a quality-of-life issue for drivers; it is an environmental and climate issue as well.

Researchers have identified two primary ways that AV technology could help reduce congestion—and therefore vehicle emissions—in cities and on highways: by making driving patterns more efficient and by averting crashes that cause severe traffic jams. Uncertainty remains, however. The potential benefits depend in part on the level of fleetwide automation achieved and whether the vehicles are able to communicate with each other and their surrounding infrastructure.[60] Moreover, AVs could cause congestion to increase in the short term before easing in the long term.

AV technology could help reduce congestion by making driving patterns more efficient and averting crashes that cause severe traffic jams.

As described above, RAND concluded that AVs might lead to more vehicles on the road in some areas as the opportunity cost of driving falls. This could increase congestion. RAND also found, however, that AV technology could help to avoid inefficient driving conditions, such as abrupt stops and starts common in heavy traffic. Even at higher speeds on highways, dramatic braking and other human reactions can cause congestion. Without these reactions, cars could travel close together safely. In essence, more cars could get through the same limited number of lanes more easily with automation technology, reducing congestion and streamlining the overall driving process.[61] RAND also found that automation—especially at levels 3 and 4—could reduce the number of automobile accidents and, therefore, the traffic backups that often accompany them.[62] As with other factors, these potential benefits depend on what portion of cars on the road are AVs.

Volvo researchers conducting a study in Sweden also found that automation could allow cars to travel more closely to each other at high speeds without compromising safety, thereby reducing congestion. The company's analysis predicts that even at higher speeds, braking can occur simultaneously thanks to enhanced vehicle-to-vehicle communication, if employed in fully autonomous vehicles or vehicles with high levels of automation and a human driver.[63]

For the past few years, Oak Ridge National Laboratory has also been looking into the effects of automation on congestion—and the potential positive impact on reducing emissions. As of 2014, researchers at Oak Ridge were developing algorithms for communication among autonomous vehicles. Implementing these algorithms, according to Andreas Malikopoulos of the laboratory's Urban Dynamics Institute, would eliminate traffic jams by allowing the cars to talk to each other. In an interview with *Scientific American* about his research, Malikopoulos explained, "Based on this instruction, you will never get in a traffic jam. … If all vehicles are coordinated, they will never have to come to a full stop or a red light."[64]

Some stakeholders warn that the congestion benefits of AVs are unlikely to occur in the short term. The Eno Center notes that many congestion benefits "may not be realized until high AV shares are present."[65] Similarly, Here, a mapping company owned by leading automakers, found that while ultimately, automation could alleviate congestion, it would not happen for decades, and congestion would increase in the near term before declining. In the next five years, some areas might experience less congestion as AVs trickle onto the roads, but then congestion would actually increase as more AVs mix in heavily with traditional vehicles. It is not until AVs saturate the market—likely 20 years to 50 years from now—that congestion would ease significantly.[66]

Some stakeholders warn that the congestion benefits of AVs are unlikely to occur in the short term.

Fuel consumption

Researchers from the Eno Center for Transportation have found that AV technology could reduce fuel consumption in the transportation sector by smoothing out driving patterns and minimizing braking.[67] This research remains speculative, as the fuel consumption benefits rely largely on the market penetration of AVs and a number of other factors. Until a large percentage of the vehicles on the road are autonomous, U.S. drivers may not realize these potential fuel savings.

According to the Eno Center's 2013 analysis, AV technologies—such as adaptive cruise control, combined with V2V communications—could smooth traffic flows and minimize braking on highways, potentially increasing fuel economy 23 percent to 39 percent, depending on assumptions about the implementation of traffic-smoothing algorithms.[68] The Eno Center also found that even if VMT increases, emissions per mile could decline if AVs can communicate with the infrastructure and drive in a smoother manner. The authors cite another study finding that with a 20 percent reduction in accelerations and decelerations, cars would consume 5 percent less fuel.[69]

Until a large percentage of the vehicles on the road are autonomous, U.S. drivers may not realize these potential fuel savings.

Zia Wadud, Don MacKenzie, and Paul Leiby have summarized existing research studies on efficient driving and fuel consumption. One study concluded that if a gasoline-powered engine was operating at its most efficient point, helped by eco-driving programming that minimizes braking, an AV could reduce fuel consumption 35 percent to 50 percent in heavily congested driving conditions, although such congestion is only occasionally found in the real world.[70] Urban driving with lots of stop-and-go traffic could see the largest increases in fuel economy, but these results will depend on the algorithms engineered into drive systems.[71] The authors caution, however, that other studies raise concerns about a "take-back effect," where eco-driving—characterized by slower speeds and gentler accelerations—could increase congestion and therefore offset potential fuel consumption benefits. They concede that it is "possible that eco-driving practices will deliver little system-wide benefit."[72]

Wadud, MacKenzie, and Leiby also looked at studies on highway platooning, in which vehicles follow each other closely on the highway, thereby decreasing the air resistance for cars following the leader. They estimated that universal adoption of platooning for light-duty vehicles—an ambitious assumption—could reduce the energy intensity of vehicles 3 percent to 25 percent. If all heavy-duty trucks platooned, a feature that automated technology could facilitate, their energy intensity would drop 10 percent to 25 percent.[73] It is unclear whether universal adoption of platooning is practical in real-world conditions, and these predictions are based on extrapolation of existing observations. Factors such as the saturation of AVs on the road and the ratio of heavy-duty trucks to light-duty vehicles could influence the impacts on fuel economy.

Researchers from Volvo published their own analysis of the effects of automated features such as platooning and adaptive cruise control, which automatically adjusts the distance between cars when driving. The authors cite a study by the European Field Operational Test, known as euroFOT, a project gathering data about intelligent transportation, which found that if every vehicle in the European Union used adaptive cruise control, it would save nearly 700 million liters of fuel each year and prevent 1.7 million tons of carbon dioxide emissions.[74] The same authors cite another study performed by Volvo itself that found that using vehicle-to-vehicle communication to platoon vehicles resulted in a 10 percent improvement in fuel economy.[75] Similarly, a 2014 study by the Intelligent Transportation Society of America predicts a 2 percent to 4 percent annual decrease in oil consumption as level 2 and 3 "intelligent transportation systems"—such as adaptive cruise control and wireless communication—spread through the automobile market.[76]

Despite these potential fuel reduction benefits, Wadud, MacKenzie, and Leiby warn that automation technology could increase the energy intensity of vehicles on the road if it encourages driving at higher speeds on the highway. Policymakers may decide to lift highway speed limits if they no longer have to factor in the human element to determine a safe speed. Highway travel accounts for 33 percent to 55 percent of all road travel; consequently, faster highway speeds could increase energy intensity 7 percent to 22 percent for all light-duty vehicles.[77]

Notably, concerns about fuel consumption are moot if autonomous vehicles on the road are electric vehicles. Wadud, MacKenzie, and Leiby suggest that automation technology could encourage the deployment of electric vehicles by eliminating an important barrier to electric vehicle adoption—the anxiety about widespread availability of refueling infrastructure. Fully autonomous vehicles could travel to fueling stations to fuel up on their own.[78]

Concerns about fuel consumption are moot if autonomous vehicles on the road are electric vehicles.

The UT Austin study offers a different perspective on fuel consumption and related emissions. Shared AVs in a connected system would be in near-constant motion, picking up and dropping off multiple passengers throughout the day, so the engine would stay warm. Each shared AV would require fewer cold starts, or times when the engine starts after remaining idle for an hour or more. Emissions are higher when the engine is cold than when the catalytic converter has warmed up, so keeping the engine warm would reduce emissions.[79]

Some automakers have argued that even low-level AV technology achieves some of these fuel economy and emissions benefits. As a result, these automakers have requested that the Environmental Protection Agency and Department of Transportation offer them credits against fuel economy and greenhouse gas tailpipe standards, potentially allowing more tailpipe pollution. See the text box for a discussion of these claims and why the agencies have not offered credits for AV technologies to date.

In 2012, the EPA and NHTSA finalized harmonized greenhouse gas and fuel economy standards for model year 2017 through 2025 passenger vehicles. These standards, which apply to passenger cars, light-duty trucks, and medium-duty passenger vehicles, promised to deliver a fleetwide tailpipe emissions standard of 163 grams of carbon dioxide per mile in model year 2025, the equivalent of 54.5 miles per gallon if achieved through fuel economy improvements.[80]

In the comment period for this rulemaking, automakers asked the EPA for credits against the tailpipe standard for their installation of crash avoidance and vehicle connectivity technologies. Companies and the Alliance of Automobile Manufacturers commented on the EPA's proposed emissions and fuel economy standards for 2017 through 2025 models in 2012 during the open comment period.[81] The Alliance noted that some eco-driving technologies can "streamline traffic flow, reduce congestion and reduce emissions" and suggested working with the agency in the future to create off-cycle credits for these technologies.[82] One company argued that it should receive credit for certain types of crash avoidance technology because it had been in the market for long enough to demonstrate that it had a statistically significant impact on crash reductions.[83]

In the final rule, the EPA denied the automakers' requests for these so-called off-cycle credits, specifically noting that they were prohibiting off-cycle credits for crash avoidance technologies "under any circumstances."[84] The EPA acknowledged that congestion mitigation helps to conserve fuel and curb carbon dioxide emissions for the entire on-road fleet. The agency expressed significant doubts, however, over "whether there is a calculable relationship between congestion mitigation and fuel/CO2 savings directly attributable to individual vehicles produced by a manufacturer, or even to a manufacturer's fleet of vehicles."[85] In this response, the EPA is noting that it would be impossible to determine how much credit to offer a specific vehicle when the congestion mitigation benefit, if any, is dispersed across all vehicles on the road. The EPA explained in detail why automakers installing certain crash avoidance technologies should not receive greenhouse gas credits:

> [F]or a technology to be "counted" under the credit provisions, it must make direct improvements to the performance of the specific vehicle to which it is applied. … The agencies believe that there is a very significant distinction between technologies providing direct and reliably quantifiable improvements to fuel economy and GHG emission reductions, and technologies which provide those improvements by indirect means, where the improvement is not reliably quantifiable, and may be speculative (or in many instances, non-existent), or may provide benefit to other vehicles on the road more than for themselves.[86]

The automakers have continued to advocate for credits for advanced vehicle technologies. In 2015, the U.S. House of Representatives Committee on Energy and Commerce considered draft legislation to require the EPA and NHSTA to offer emissions credits for certain advanced vehicle technologies. Mitch Bainwol of the Alliance of Automobile Manufacturers, testifying in support of the legislation, argued that cars equipped with crash avoidance mechanisms such as automatic braking, lane departure alerts, and adaptive cruise control—as well as vehicle-to-vehicle communication technologies—should receive credits because they help reduce congestion and emissions from idling traffic.[87] In its 2016 public comments to the EPA and NHTSA on the "Draft Technical Assessment Report" for the midterm review of the emissions and fuel economy standards, the Alliance reaffirmed its belief that these credits should be awarded.[88]

Right type and sizing

Automation technology could allow automakers to build lighter and more fuel-efficient cars. If the safety benefits of fully autonomous vehicles become a reality, automakers could remove some protective bulk from personal vehicles. This anticipated safety benefit, however, likely is dependent on widespread penetration of AVs into the vehicle market.

In their research, Wadud, MacKenzie, and Leiby found that the full benefits of right-sizing—or matching vehicle size to the number of passengers—could be best achieved through the sharing of AVs, where smaller groups or individuals can secure a ride in a smaller, more fuel-efficient car instead of riding alone in a larger, partially empty car. However, achieving these benefits assume that passenger travel is the only reason a person would use a car, ignoring the other reasons for car ownership, many of which increase vehicle weight, such as transporting cargo or carrying bicycles or skis.[89] On the other hand, the authors suggest that if high levels of automation—levels 3 and 4—allow people to be more productive in car travel, they might spend more time in the cars where they can work and relax. If consumers desire additional features in their cars for comfort, these additional features could add some weight, resulting in increased fuel consumption.[90]

The Austin study found that right-sized fleet purchase decisions for vehicles in shared AV fleets could reduce fuel use and emissions, as many vehicles used for car-sharing would be smaller, compact passenger vehicles.[91] However, the overall effect is uncertain, as smaller vehicles could limit the number of passengers in each car and increase the number of cars on the road.

The need for electrification

If the primary method of mobility is moving toward AV fleets—shared or personally owned—the best way to minimize emissions from the transportation sector is to combine vehicle automation with electrification. To achieve the nation's climate goals, the United States cannot remain dependent on gasoline-powered vehicles. A recent report by Climate Action Tracker concludes that zero-emission vehicles must take over the global market by 2035, coupled with reducing emissions from the power sector, in order to limit global warming to 1.5 degrees Celsius—the internationally agreed-upon target set at the end of 2015 with the Paris climate agreement.[92] If 50 percent of cars on the road globally are electric by 2050 and fuel economy standards are doubled by 2030—again, in parallel with power sector emissions reductions—then it might be possible for global warming to be limited to 2 degrees Celsius, which is the upper—and less desirable—target of the Paris agreement.[93]

Recommendations for additional research

While researchers are beginning to examine the potential environmental impacts of autonomous vehicle deployment, more research is needed to fully understand how automation of the light-duty vehicle sector will affect carbon emissions and the climate. The Center for American Progress offers the following recommendations for additional research on vehicle-miles traveled, travel patterns, and gasoline use in AVs.

Impact of gradual adoption on emissions

Studies of environmental benefits often assume that every car is fully automated and shared and do not take into account a transition period in which humans still drive some of the vehicles on the road. A transportation system that is fully automated and dominated by car- and ride-sharing services is unlikely to occur for decades. Until that time, the number of vehicles and drivers on the road may increase along with emissions at precisely the time that the United States needs to be bending the emissions curve downward. More research is needed to study the impacts of incremental introduction of AVs to the country's roadways; how gradual adoption of this technology might affect carbon emissions levels from the transportation sector; and how this relates to the country's need to significantly cut emissions in the short term.

Systems-based research

More research is needed to understand how AVs will fit within the whole transportation and infrastructure system. In particular, researchers should examine the relative benefits and costs of investment in AVs compared with similar investment in public transit—another option for reducing vehicles on the road and cutting emissions from the transportation sector. Automakers and tech companies are driving the transition to a transportation system reliant on autonomous vehicles, but it is unclear whether that is the most efficient choice from an emissions-reduction perspective. Policymakers need a better understanding of how AVs and public transportation can work together to cut carbon pollution from light-duty vehicles and how policymakers should direct transportation investment in order to achieve the maximum environmental benefit.

Travel patterns and driver behavior

One major area of uncertainty is the total effect of AVs on VMT. The existing research shows conflicting conclusions about whether AV deployment will reduce or induce travel demand. The challenge lies in the number of assumptions that factor into whether AVs will be a net positive or detriment to the climate: whether AVs will add new classes of drivers to the road, remove cars from the road through car-sharing, encourage people to commute from farther distances, or make vehicle-based transportation more efficient. Researchers need to compile more information about how automation would affect the social cost of driving if the driver can do other things, such as work, while traveling and how that would change driver behavior and choices. Overall, researchers do not appear to have the analytical tools needed to model this complex array of assumptions and identify the range of potential outcomes.

Experts should invest in new modeling capabilities to predict how these factors would interact; this would give policymakers a window into how to avoid potential pitfalls during the transition to an automated transportation system.

Electrification of AVs

Electrifying the autonomous vehicle fleet would alleviate concerns about new emissions from the transportation sector, assuming that the electricity sector continues to decarbonize. Policymakers and stakeholders would benefit from a deeper understanding of how the electrification of the transportation system—which must happen to achieve the nation's climate pollution reduction goals—can proceed in tandem with the automation of vehicles.

Electrification and automation of the transportation sector could require significant investment in infrastructure to support the new technologies. Further research should uncover what this infrastructure buildout would entail and how policymakers can ensure that it proceeds systematically and efficiently.

Technological questions remain as well. For example, additional research may be necessary to examine how combining automation with electrification could affect vehicle performance, including battery life and driving range of EVs.

Additional consumer research should shed light on how automation supports electrification and vice versa. Researchers, for example, could build on existing studies suggesting that consumers may be more accepting of electric vehicles if they are autonomous—and therefore able to fuel themselves. This could give policymakers new insight into how to design better incentives to expedite the electrification of the transportation sector.

Data collection and sharing

The National Association of City Transportation Officials, or NACTO, has recommended some areas of analysis needed to improve the quality, quantity, and sharing of traffic data. They suggest directing federal and state funds to research on city operations of shared autonomous electric vehicles, as city streets require algorithms to address the most complex problems inhibiting smooth driving. Research in this arena should focus on what city infrastructure is needed to facilitate driving with traits that would enhance car-sharing, as well as efficient driving to reduce emissions.[94]

NACTO also recommends implementing a modeling exercise similar to a study performed in Lisbon, Portugal, by the International Transport Forum in 2015. The Lisbon model predicts various ways that shifts in transportation costs will influence patterns in travel. A similar modeling exercise would be very beneficial for studying the impacts of different advanced vehicle technologies in North America, which would allow policymakers to tailor policy promoting zero-carbon vehicle technology accordingly.[95] This type of modeling could also help researchers compare the effects of automation on travel patterns with the effects of expanded public transit.

Conclusion

Automakers, tech giants, and ride-sharing companies are spearheading a significant transition in the transportation sector. Companies across the spectrum are developing cars and supporting technology that will eventually allow cars to drive themselves. As this technology advances, it is critical that researchers and policymakers carefully examine the effects of these autonomous vehicles not only on safety and personal mobility but on the environment as well—particularly as they relate to the fight against climate change. While some research exists on how AVs will affect driving patterns, congestion, and accidents, further research is necessary to tease out whether AV deployment will increase or decrease vehicle carbon emissions. Under some circumstances, AVs could increase the number of miles Americans drive each year—and therefore increase emissions. In other scenarios, AVs could make driving more efficient and less polluting. All that is certain is that uncertainty remains as to whether automation of vehicles will help the United States respond to climate change.

Policymakers, automakers, and tech companies need to invest in additional research to clarify the environmental and climate impacts of automation. At the same time, they should recognize that ensuring that autonomous vehicles are electric, rather than gasoline-powered, would render concerns about tailpipe emissions moot. Electric vehicles are the logical choice for a cleaner transportation future—automated or not.

About the authors

Myriam Alexander-Kearns is a Research Associate for the Energy Policy team at the Center for American Progress.

Miranda Peterson is a Research Assistant for the Energy Policy team at the Center.

Alison Cassady is the Director of Domestic Energy Policy at the Center.

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