Testimony

Shaping the Future of Autonomous Vehicles

How Policymakers Can Promote Safety, Mobility, and Efficiency in an Uncertain World

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CT-459

Testimony presented before the Senate Appropriations Committee, Subcommittee on Transportation, Housing and Urban Development, and Related Agencies on November 16, 2016.

Published by the RAND Corporation, Santa Monica, Calif.

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Before the Committee on Appropriations
Subcommittee on Transportation, Housing and Urban Development, and Related Agencies
United States Senate

November 16, 2016

Chairman Collins, Ranking Member Reed, and distinguished members of the subcommittee, thank you for the opportunity to testify on important emerging opportunities and risks related to autonomous vehicles. Autonomous vehicles have the potential to change transportation profoundly, in the United States and around the world. There is much opportunity for improvement, but also potential for added risks and harms. How autonomous vehicles ultimately shape our future is not foretold; it depends on many technology and policy choices we make today.

Today, I would like to discuss three important questions about the future of autonomous vehicles and how policies can shape it. First, will autonomous vehicles be safe before they are allowed on the road for consumer use? Second, how can autonomous vehicles improve mobility for Americans who currently may have limited mobility? Third, what mechanisms can help realize the benefits and mitigate the drawbacks of autonomous vehicles? I will focus most of my remarks on fully autonomous vehicles—those that can operate without a human driver some or all of the time—rather than on vehicles that require continuous human oversight.

Will Autonomous Vehicles Be Safe Before They Are Allowed on the Road for Consumer Use?

In the United States, roughly 32,000 people are killed and more than 2 million are injured in motor vehicle crashes every year.[2] Although safety has generally improved over the past several

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decades, 2015 saw 35,000 road fatalities, the largest increase in fatalities in this country in more than 50 years. This occurred partly because Americans drove more and partly because they drove worse.

U.S. motor vehicle crashes as a whole can pose enormous economic and social costs—more than $800 billion in a single year.[3] And more than 90 percent of crashes are caused by human errors,[4] such as driving too fast and misjudging other drivers' behaviors, as well as alcohol impairment, distraction, and fatigue.

Autonomous Vehicles Present Benefits and Risks to Safety

Autonomous vehicles have the potential to significantly mitigate this public safety crisis by eliminating many of the mistakes that human drivers routinely make.[5] To begin with, autonomous vehicles are never drunk, distracted, or tired; these factors are involved in 41 percent, 10 percent, and 2.5 percent, respectively, of all fatal crashes.[6] Autonomous vehicles could perform better than human drivers because of better perception (e.g., no blind spots), better decisionmaking (e.g., more-accurate planning of complex driving maneuvers), and better execution (e.g., faster and more-precise control of steering, brakes, and acceleration).

However, autonomous vehicles might not eliminate all crashes. For instance, inclement weather and complex driving environments pose challenges for autonomous vehicles, as well as for human drivers, and autonomous vehicles might perform worse than human drivers in some cases.[7] There is also the potential for autonomous vehicles to pose new and serious crash risks—

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[2] Bureau of Transportation Statistics, *Motor Vehicle Safety Data*, Table 2-17, Washington, D.C.: Research and Innovative Technology Administration, U.S. Department of Transportation, 2015.

[3] Lawrence Blincoe, Ted R. Miller, Eduard Zaloshnja, and Bruce A. Lawrence, *The Economic and Societal Impact of Motor Vehicle Crashes 2010 (Revised)*, Washington, D.C.: National Highway Traffic Safety Administration, DOT HS 812 013, 2014, revised May 2015.

[4] National Highway Traffic Safety Administration, *Traffic Safety Facts, A Brief Statistical Summary: Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey*, Washington, D.C.: National Center for Statistics and Analysis, U.S. Department of Transportation, DOT HS 812 115, February 2015.

[5] James M. Anderson, Nidhi Kalra, Karlyn D. Stanley, Paul Sorensen, Constantine Samaras, and Oluwatobi A. Oluwatola, *Autonomous Vehicle Technology: A Guide for Policymakers*, Santa Monica, Calif.: RAND Corporation, RR-433-2-RC, 2014; and Daniel J. Fagnant and Kara Kockelman, "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations," *Transportation Research Part A: Policy and Practice*, Vol. 77, July 2015, pp. 167–181.

[6] National Highway Traffic Safety Administration, *Traffic Safety Facts: Crash Stats*, Washington, D.C.: National Center for Statistics and Analysis, DOT HS 811 449, March 2011; Bureau of Transportation Statistics, *Occupant and Non-Motorist Fatalities in Crashes by Number of Vehicles and Alcohol Involvement (Updated July 2014)*, Table 2–20, Washington, D.C.: U.S. Department of Transportation, 2014; and U.S. Department of Transportation, *Fact Sheet: Enhanced Mobility of Seniors and Individuals with Disabilities Section 5310*, Washington D.C., 2015. This does not mean that 53.5 percent of all fatal crashes are caused by these factors because a crash may involve, but not be strictly caused by, one of these factors, and because more than one of these factors may be involved in a single crash.

[7] Lee Gomes, *Hidden Obstacles for Google's Self-Driving Cars: Impressive Progress Hides Major Limitations of Google's Quest for Automated Driving*, Massachusetts Institute of Technology, August 28, 2014.

for example, crashes resulting from cyber attacks.[8] Clearly, autonomous vehicles present both enormous potential benefits and potential risks to transportation safety.

When the National Highway Traffic Safety Administration released much-anticipated guidelines intended to outline best practices for autonomous vehicle safety, many looked to that guidance to answer the key question: Will autonomous vehicles be safe? I believe the answer is "maybe." Answering the question requires considering two issues. First, how should autonomous vehicle safety be measured, and second, what threshold of safety should be required before autonomous vehicles are made publicly available? In essence, what test do autonomous vehicles have to take and what constitutes a passing grade? Both are genuinely open questions, so it is understandable that federal guidelines have not yet answered them

There Is No Proven, Feasible Way to Determine Autonomous Vehicle Safety

There are no road tests that could demonstrate how safe an autonomous vehicle is—there are too many conditions and scenarios to test them all. (A road test that a person takes at the Department of Motor Vehicles also does not prove that he or she will be a good driver; rather, the road test determines whether the person can perform a specific set of driving skills under regular traffic situations. While this type of evidence is viewed as adequate for licensing human drivers, it is not generally viewed as adequate for robot drivers.)

A logical alternative is to test-drive autonomous vehicles extensively in real traffic and observe their performance before making them commercially available. Although this is a helpful first step, it is not sufficient to prove safety. Even though the number of crashes, injuries, and fatalities from human drivers is high, the rate of these failures is low *in comparison with the number of miles that people drive*. Americans drive nearly 3 trillion miles every year.[9] The 35,092 fatalities and 2.44 million injuries in 2015 correspond to a failure rate of 1.12 fatalities and 78 injuries per 100 million miles driven. Given that current traffic fatalities and injuries are rare events compared with vehicle miles traveled, fully autonomous vehicles would have to be driven hundreds of millions of miles and sometimes hundreds of billions of miles to demonstrate their reliability in terms of fatalities and injuries. Under even aggressive testing assumptions, existing fleets would take tens and sometimes hundreds of years to drive these miles—an impossible proposition if the aim is to demonstrate their performance prior to releasing them on the roads for consumer use.[10] And, in the meantime, human drivers would continue to cause avoidable crashes and enormous harms to people and property.

Developers of this technology and third-party testers need to develop innovative methods of demonstrating safety and reliability. These methods may include but are not limited to accelerated testing,[11] virtual testing and simulations,[12] mathematical modeling and analysis,[13]

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[8] Anderson et al., 2014.

[9] Bureau of Transportation Statistics, 2015.

[10] Nidhi Kalra and Susan M. Paddock, *Driving to Safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability?* Santa Monica, Calif.: RAND Corporation, RR-1478-RC, 2016.

[11] Wayne B. Nelson, *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*, Hoboken, N.J.: John Wiley & Sons, 2009.

scenario and behavior testing,[14] and pilot studies,[15] as well as extensive focused testing of hardware and software systems. This is a rapidly growing area of research and development. There are promising ideas but no demonstrated and accepted methods of proving safety. In sum, no one yet knows how autonomous vehicles should be tested. It is therefore reasonable that the current federal guidelines have not specified a test either.

There Is No Consensus on How Safe Autonomous Vehicles Should Be

The second issue of how safe autonomous vehicles should be is worth considering, even if their degree of safety cannot yet be fully proven. Some will insist that anything short of totally eliminating risk is a safety compromise. They might feel that it is acceptable if humans make mistakes, but not if machines do. But, again, waiting for autonomous vehicles to operate perfectly misses opportunities to save lives because it leaves far-from-perfect human drivers behind the wheel.

It seems sensible that autonomous vehicles should be allowed on America's roads when they are judged safer than the average human driver, allowing more lives to be saved and sooner while still ensuring that autonomous vehicles do not create new risks. An argument can be made that autonomous vehicles could be allowed even when they are not as safe as average human drivers if developers can use early deployment as a way to rapidly improve the vehicles. The vehicles could become at least as good as the average human sooner than they would otherwise, and thus save more lives overall.

The lack of consensus on this point is not a failure of sound thinking. It is not a failure at all, but rather a genuine expression of Americans' different values and beliefs when it comes to humans versus machines. It is therefore reasonable that the federal guidelines also do not draw a line in the sand.

While these are difficult decisions, our differences in values and beliefs can be informed by thinking not only about safety today but also about the arc of safety in the coming decades. Our

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[12] Suren Chen and Feng Chen, "Simulation-Based Assessment of Vehicle Safety Behavior under Hazardous Driving Conditions," *Journal of Transportation Engineering*, Vol. 136, No. 4, 2010, pp. 304–315; Siddartha Khastgir, Stewart A. Birrell, Gunwant Dhadyalla, and Paul A. Jennings, "Development of a Drive-In Driver-in-the-Loop Fully Immersive Driving Simulator for Virtual Validation of Automotive Systems," paper presented at IEEE 81st Vehicular Technology Conference, Glasgow, Scotland, May 11–14, 2015; and Stephanie Olivares, Nikolaus Rebernik, Arno Eichberger, and Ernst Stadlober, "Virtual Stochastic Testing of Advanced Driver Assistance Systems," in Tim Schulze, Beate Müller, and Gereon Meyer, eds., *Advanced Microsystems for Automotive Applications 2015: Smart Systems for Green and Automated Driving*, New York: Springer, 2015.

[13] Khashayar Hojjati-Emami, Balbir Dhillon, and Kouroush Jenab, "Reliability Prediction for the Vehicles Equipped with Advanced Driver Assistance Systems (ADAS) and Passive Safety Systems (PSS)," *International Journal of Industrial Engineering Computations*, Vol. 3, No. 5, 2012, pp. 731–742; and R. Kianfar, P. Falcone, and J. Fredriksson, "Safety Verification of Automated Driving Systems," *IEEE Intelligent Transportation Systems Magazine*, Vol. 5, No. 4, Winter 2013, pp. 73–86.

[14] California Department of Motor Vehicles, *Express Terms Title 13, Division 1, Chapter 1 Article 3.7—Autonomous Vehicles*, 2015; and Michael Sivak, and Brandon Schoettle, *Should We Require Licensing Tests and Graduated Licensing for Self-Driving Vehicles?* University of Michigan: Transportation Research Institute, Technical Report UMTRI-2015-33, 2015.

[15] ANWB, *Experiments on Autonomous and Automated Driving: An Overview 2015*, 2015.

discourse on the question of how safe the vehicles need to be focuses on the safety of autonomous vehicles at the time that they are first introduced for consumer use. But this thinking should be expanded to consider the *evolution* of autonomous vehicle safety over time, not just at the start of vehicle deployment. When a human driver makes a mistake on the road, typically only that individual can learn from that experience to improve his or her driving habits. The other drivers on the road are largely unaffected. This is not the case with autonomous vehicles, which can use experience and learning to improve performance, not just of the individual vehicle but of the entire fleet. This is because, when an algorithm or software is updated and improved for one vehicle, it can be updated for all vehicles. For this reason, experience may be one of the most important tools for improving autonomous vehicle safety and, by extension, transportation safety.

Policymakers Can Promote Autonomous Vehicle Safety

This raises an important question: How do we enable autonomous vehicles to improve as quickly as possible while lowering the risks they pose? There are several tactics policymakers could consider to accelerate autonomous vehicles' improvement.

A first step is to conduct real-world but lower-risk pilot studies of autonomous vehicles. Risk can be lowered first by operating autonomous vehicles in conditions in which crashes are less likely. This can include limiting autonomous vehicle pilots to areas with less-complex terrain, to routes that are well maintained and easier to navigate, to nondangerous weather conditions, or to some combination of these controls. It can also include educating communities about safe behavior in and around autonomous vehicles. Furthermore, risk can be lowered by designing and operating vehicles so that when crashes occur, the consequences of the crash to passengers and bystanders are fewer. This could be accomplished by limiting vehicle speed, ensuring that all pilot-study passengers wear seatbelts, and so forth. These strategically limited pilot studies can then be expanded as safe operation of autonomous vehicles is demonstrated.

A second consideration is the role of sharing driving data across the industry and with policymakers. Autonomous vehicle developers already use the experiences of a single vehicle to improve the safety of their individual fleets. This improvement could occur even faster if the experiences of each vehicle in each fleet could be used across all developers to improve the entire industry. There are certainly nontrivial concerns about protecting trade secrets, but these concerns could be addressed and must be balanced with the societal need for safe autonomous vehicle technology.

In sum, it may not be possible to know what the safety risk of autonomous vehicles is, and Americans may not agree on what it should be. All the same, there are ways of *lowering* that risk that deserve careful consideration.

How Can Autonomous Vehicles Improve Mobility for Americans Who Currently May Have Limited Mobility?

For almost all Americans, the ability to get around is essential for living a rich, productive, and healthy life: being able to get to a place of work, to visit friends and family, to access health care and other services, to participate in civic activities, and to be connected to the external world in all other ways. Even with the increasing ability to interact and transact online, the importance of mobility in today's world remains vital. Despite its importance, many Americans have limited, and sometimes very limited, mobility as a result of advanced age, disabilities, or lack of means. Whatever the reason, limited mobility has significant negative consequences. Autonomous vehicles could help.

Autonomous Vehicles Could Help Many Older Americans Who Face Limited or Declining Mobility

The experiences of older Americans, especially those over 75, are emblematic of the challenges of limited mobility. The number of Americans 65 and older will increase from 48 million in 2015 (15 percent of today's population) to 74 million in 2030 (23 percent of the population). The number of Americans 75 and older will increase from 20 million in 2014 (6 percent of today's population) to 35 million in 2030 (10 percent of the population.)[16] Older Americans are living longer and working longer than ever before. The labor force participation of those over 65 is expected to be 21.7 percent in 2024, up from 12.4 percent in 1994.[17]

Driving is important to their quality of life. Of adults over 65, 80 percent live in car-dependent areas and 90 percent say they intend to age in place.[18] Eighty-five percent of adults aged 65 to 84 hold licenses, and almost 60 percent of adults over 85 hold licenses.[19]

Driving is risky for many older Americans. A recent study found that, when compared with drivers aged 55 to 64, drivers over 75 were more than 2.5 times as likely to die in a car crash, and drivers over 85 were almost four times as likely.[20] This is due both to increased likelihood of getting into crashes and greater vulnerability to injuries.

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[16] U.S. Census Bureau, *Projections of the Population by Sex and Age for the United States: 2015 to 2060 (NP2014-T9)*, spreadsheet, December 2014. As of November 8, 2016:
http://www.census.gov/population/projections/files/summary/NP2014-T9.xls

[17] Bureau of Labor Statistics, "Civilian Labor Force Participation Rate by Age, Gender, Race, and Ethnicity," web page, December 2015. As of November 8, 2016:
http://www.bls.gov/emp/ep_table_303.htm

[18] David Dudley, "The Driverless Car Is (Almost) Here," *AARP The Magazine*, December 2014/January 2015. As of November 8, 2016:
http://www.aarp.org/home-family/personal-technology/info-2014/google-self-driving-car.html

[19] Policy and Governmental Affairs Office of Highway Police Information, "Distribution of Licensed Drivers – 2014 By Sex and Percentage in Each Age Group and Relation to Population," web page, U.S. Department of Transportation, September 2014. As of November 8, 2016:
https://www.fhwa.dot.gov/policyinformation/statistics/2014/dl20.cfm

[20] AAA Foundation for Traffic Safety, "Drivers Over 65 Almost Twice as Likely as Middle-Aged Drivers to Die in Car Crashes, According to AAA Foundation Study," February 18, 2004. As of November 8, 2016:
https://www.aaafoundation.org/sites/default/files/DriversOver65.pdf

But giving up driving has risks as well. Driving cessation almost doubles the risk of increased depressive symptoms and is correlated with (though not strictly a cause of) cognitive, social, and physical declines and higher rates of entry into long-term care.[21]

Geography can further affect mobility. Approximately 18 percent of the rural population is 65 years or older, compared with 13.5 percent in non-rural areas.[22] Compared with their counterparts in urban areas, older adults in rural areas must take longer trips for health care and other services and have fewer alternatives to driving.[23]

Autonomous vehicles offer a promising solution. Fully automated vehicles that do not require human intervention would allow many older adults to travel by car, without having to drive. It could increase their mobility, with all of the associated social and economic benefits, while mitigating much of the safety risk. This, in turn, may allow more people to age in place, remaining in their homes for much longer than they might otherwise be able to.

Autonomous Vehicles Could Improve Mobility for Many Others

Older adults are just one group of Americans that could benefit from increased mobility from autonomous vehicles. Many people with disabilities, young people, and people living in poverty face mobility challenges that could be alleviated by autonomous vehicles.

In 2010, 56.7 million individuals (18.7 percent of the population) identified as having a disability.[24] Only 65 percent of individuals with disabilities drive, compared with 88 percent of individuals without disabilities.[25] In spite of the Americans with Disabilities Act, which mandates that transit authorities operating a fixed route system provide paratransit or a comparable service to individuals with a disability,[26] individuals with disabilities often have limited mobility because of a lack of availability or access to services. One survey showed that 12 percent of persons with disabilities reported having a harder time obtaining the transportation they need to be independent, compared with 3 percent of others, the top two reasons being no or limited public transportation (33 percent) and not having a car (26 percent).[27]

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[21] Stanford Chihuri, Thelma J. Mielenz, Charles J. DiMaggio, Marian E. Betz, Carolyn DiGuiseppi, Vanya C. Jones, and Guohua Li, “Driving Cessation and Health Outcomes in Older Adults,” American Geriatric Society, Vol. 64, 2016, pp. 332–341.

[22] U.S. Census Bureau, “Percent of the Total Population Who Are 65 Years and Over – United States – Urban/Rural and Inside/Outside Metropolitan and Micropolitan Area,” American FactFinder, 2014. As of November 8, 2016: http://factfinder.census.gov/bkmk/table/1.0/en/ACS/14_5YR/GCT0103.US26

[23] J. E. Burkhardt, A. T. McGavock, C. A. Nelson, and C. G. B. Mitchel, *Improving Public Transit Options for Older Persons Transit Cooperative Research Program*, Washington D.C.: Transport Research Board, 2002.

[24] Matthew W. Brault, *Americans with Disabilities: 2010,* U.S. Census Bureau, July 2012.

[25] U.S. Department of Transportation, *Freedom to Travel*, Washington D.C.: Bureau of Transportation Statistics, 2003.

[26] U.S. Department of Justice, Information and Technical Assistance on the Americans with Disabilities Act, 2016.

[27] U.S. Department of Transportation, 2003.

There are also 25 million young Americans between the ages of 12 and 17 who have mobility needs but are not yet old enough to drive or are novice drivers.[28] Getting to school and academic enrichment opportunities, social and extracurricular activities, and even first jobs can be a challenge. Many depend on buses (principally to school) or their parents—or forgo travel. For many working parents, there is a trade-off between supporting their own and their children's mobility needs.

Americans living in poverty also face mobility challenges. About 43.1 million people (13.3 percent of the population) live in poverty.[29] This includes older adults and many individuals with disabilities. In 2014, 10 percent of older adults and 28.5 percent of individuals with a disability had a yearly income below the poverty line.[30]

About 24 percent of households below the poverty line do not own a vehicle, compared with just 2 percent of households with incomes over $100,000. Individuals living in poverty are about three times as likely to take transit and 1.5 times more likely to walk.[31] While these are desirable ways to get around for environmental and physical health reasons, they can take much more time and limit travel to destinations that are accessible by these modes. This is important because research shows that access to efficient transportation is important for escaping poverty (via access to education, training, and work) and achieving upward economic mobility.[32] In sum, there are millions of Americans with limited mobility, and autonomous vehicles could help them.

Affordability, Availability, and Accessibility Are Keys to Realizing These Benefits

Simply bringing autonomous vehicles to market might not fully solve the mobility challenges Americans face. Autonomous vehicles, like other transportation options, must also be affordable, available, and accessible. Fortunately, autonomous vehicles may have advantages over conventional transit, taxi, or vehicle-sharing services.

For many older adults, individuals with disabilities, and other people living below the poverty line, the costs of a personally owned vehicle are prohibitive. The costs of a privately owned autonomous vehicle are expected to be much higher, particularly initially. Shared autonomous vehicles will be the key to affordability. Shared vehicles are vehicles that are not personally owned but instead are available for many people to use, either on demand or through a reservation system, and are typically pay-per-use. Some estimates suggest that the per-mile

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[28] Federal Interagency Forum on Child and Family Statistics, "POP1 Child Population: Number of Children (in millions) Ages 0–17 in the United States by Age, 1950–2015 and Projected 2016–2050," 2016. As of November 8, 2016:
http://www.childstats.gov/americaschildren/tables/pop1.asp

[29] Bernadette D. Proctor, Jessica L. Semega, and Melissa A. Kollar, *Income and Poverty in the United States: 2015*, U.S. Census Bureau, September 2016. As of November 8, 2016:
http://www.census.gov/library/publications/2016/demo/p60-256.html

[30] C. DeNavas-Walt and B. D. Proctor, *Income and Poverty in the United States: 2014*, Washington D.C.: U.S. Census Bureau, 2015.

[31] Federal Highway Administration, "Mobility Challenges for Households in Poverty: 2009 National Household Travel Survey," FHWA NHTS Brief, 2014.

[32] Raj Chetty and Nathaniel Hendren, "The Impacts of Neighborhoods on Intergenerational Mobility: Childhood Exposure Effects and County-Level Estimates," Harvard University, 2015.

cost of using a shared autonomous vehicle service could be 30 percent to 90 percent less than owning a conventional vehicle or using conventional taxis, depending on the nature of the service.[33] In other words, the per-trip costs could be comparable to transit, but with greater convenience and speed.

Second, shared autonomous vehicles must be available where people live. Car-sharing vehicles and taxis are not readily available in most small towns and rural communities because there are too few people to support the services. Furthermore, those who live in poor urban areas are another underserved segment in today's mobility market. Transit may not offer complete solutions, and taxis have historically been scarce because of the low demand compared to wealthier urban areas.[34] The lower cost of shared autonomous vehicles may increase the availability in underserved regions where other transportation solutions are limited.

Third, shared autonomous vehicles need to be accessible. This includes vehicle design, websites, and technology interfaces that are consistent with Americans with Disabilities Act and other accessibility standards and guidelines. It also includes implementing diverse payment systems that do not require smart phones or credit cards. Meeting these design goals can be expensive. For example, the National Highway Traffic Safety Administration estimates that the cost of a new vehicle with adaptive equipment (e.g., mechanical hand controls, power transfer seats, and lifts and ramps) can be \$20,000–\$80,000.[35] The cost for accessible autonomous vehicles may be lower because the vehicle only needs to be modified for passenger use; it does not need to be modified to enable driving.

Policymakers Can Promote Affordability, Availability, and Accessibility

All of this suggests that autonomous vehicles may increase mobility for historically underserved populations in a way that is more affordable, available, and accessible than existing transportation options. However, there is a clear and essential role for sound policy in realizing these benefits.

First, policymakers can create incentives for manufacturers to prioritize these markets and reach them sooner than they might otherwise. Incentives can include cost-sharing programs, subsidies, or other financial levers. They can also include partnerships to integrate both public and private shared autonomous vehicles into existing transit and paratransit services so that they are complementary rather than competing. This may involve making payment seamless across

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[33] Lawrence D. Burnes, William C. Jordan, and Bonnie A. Scarborough, *Transforming Personal Mobility*, The Earth Institute, Columbia University, January 27, 2013; and Tasha Keeney, "What If Uber Were to Adopt Shared Autonomous Vehicles (SAVs)?" ARK Invest, June 22, 2015.

[34] Mark W. Frankena and Paul A. Pautler, *An Economic Analysis of Taxicab Regulation*, Bureau of Economics, No. 1103, May 1984; Nelson Nygaard, *Boston Taxi Consultant Report*, 2013; and Hara Associates Inc., *Best Practices Studies of Taxi Regulation: Taxi User Surveys*, prepared for San Francisco Municipal Transportation Agency, 2013. Today's ride share services may be helping provide better service in these underserved populations (see the Uber-funded study by Rosanna Smart, Brad Rowe, Angela Hawken, Mark Kleiman, Nate Mladenovic, Peter Gehred, and Clarissa Manning, *Faster and Cheaper: How Ride-Sourcing Fills a Gap in Low-Income Los Angeles Neighborhoods*, BOTEC Analysis Corporation, July 2015).

[35] National Highway Traffic Safety Administration, *Adapting Motor Vehicles for People with Disabilities*, June 2015.

modes, providing transfer benefits across modes, and integrating scheduling. Private ride-share services are already working with transit agencies to provide connections to existing transit services, but primarily in urban areas.

Second, policymakers may need to incentivize technology developers to ensure that accessibility for diverse populations is a priority when designing these vehicles. This includes facilitating collaboration between developers, health care providers, independent living centers and other facilities, and, most importantly, the users themselves. Participatory design will be key.

Third, while the cost of shared autonomous vehicles is expected to be lower than many alternatives, public assistance may still be warranted. In many regions, seniors and individuals with disabilities ride transit at a discounted rate or even for free. Policies would be needed to extend these discounts to shared autonomous vehicle services.

In sum, autonomous vehicles present an enormous opportunity to improve mobility for millions of Americans who are currently underserved by our existing transportation system. The social, health, and economic benefits could be enormous. Policymakers can play an important and distinct role in prioritizing and enabling the technology so that autonomous vehicles can help democratize America's transportation system.

What Mechanisms Can Help Realize the Benefits and Mitigate the Drawbacks of Autonomous Vehicles?

In addition to transforming safety and mobility, autonomous vehicles may also shape other areas of transportation, including congestion, energy and pollution, and land use. Some potential impacts will be positive while others will be negative. All of the impacts are complex and difficult to predict, but despite the uncertainty, policymakers can help nudge the free market in the right direction.

The Impacts of Autonomous Vehicles on Congestion

Congestion has enormous societal costs. Travel delays resulting from traffic congestion caused drivers to waste more than 3 billion gallons of fuel and kept travelers stuck in their cars for nearly 7 billion extra hours—42 hours per rush-hour commuter.[36] The total cost to the United States was $960 per commuter, or $160 billion for the nation as a whole.

Even if autonomous vehicles had no impact on the incidence of congestion, they could reduce the *cost* of congestion. If individuals can work in their cars, the cost of the time spent in traffic could be reduced substantially, even if the time itself is not reduced.

Nevertheless, the potential impact of autonomous vehicles on traffic congestion itself could be substantial but is uncertain. Traffic congestion could be significantly reduced because more vehicles can fit on a given stretch of roadway if they are autonomous. In the near term, autonomous vehicle platooning (where cars drive close together to reduce air resistance and increase fuel economy) can enable greater throughput; in the longer term, if a large number of

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[36] David L. Schrank, Bill Eisele, and Timothy J. Lomax, *The 2015 Urban Mobility Scorecard*, College Station, Tex.: Texas A&M Transportation Institute, 2015.

vehicles are autonomous, lanes could be made narrower, creating more usable road space. If autonomous vehicles are much safer, they could significantly reduce crashes, which are a major source of congestion. Shared autonomous vehicles could provide better connections to main transit lines, leading to increases in use.[37]

However, there is a flip side. Because autonomous vehicles will lower the costs of driving by car—by enabling productivity in the vehicle, reducing fuel costs through greater fuel economy, avoiding parking fees, and lowering insurance costs through greater safety—they could also increase the amount of driving. Improvements in mobility for underserved populations would also add to the amount of driving. If people can do the same things from the comfort of their own cars, fewer people might take public transit.[38]

Accurately predicting the net effect on transportation demand is impossible because of the disruptive nature of autonomous vehicles. Just as we could not predict in 1990 how the Internet would change how and how much we would communicate 20 years later, we cannot confidently predict today how autonomous vehicles will change how and how much we will travel 20 years from now.

The Impacts of Autonomous Vehicles on Energy

Autonomous vehicles could increase fuel efficiency, but the net effect is unclear because they may increase travel demand, which could negate those gains. To the extent that fossil fuels remain the primary source of transportation energy, this would have knock-on effects in foreign oil dependence, air pollution, and greenhouse gas emissions.

The way people operate and maintain vehicles is inefficient. Aggressive driving alone can drop fuel economy by 25 percent, and not using cruise control on highways can drop it another 7 percent.[39] Autonomous vehicles can avoid these behaviors and thus reduce fuel consumption. Adding to this, even relatively simple levels of automation can enable platooning.

In the longer term, if autonomous vehicles that crash less are widely used, they could be built lighter, which will further reduce fuel consumption and emissions. Less obviously, fully autonomous vehicles might be able to jump-start alternative transportation fuels. One of the key obstacles to both plug-in electric and hydrogen fuel cells, which have zero tailpipe emissions and can use renewable energy, is the lack of refueling or charging infrastructure. This becomes much less of a problem if cars can drive themselves to refueling or recharging stations because far fewer stations are needed.[40] One recent study showed that electric shared autonomous vehicles could reduce greenhouse gas emissions in 2030 by 87–94 percent relative to current conventional vehicles and 63–82 percent below projected model year 2030 hybrid vehicles because of

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[37] Johanna Zmud, Jason Wagner, Richard T. Baker, Ginger Goodin, Maarit Moran, Nidhi Kalra, and Dan Fagnant, *Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems in Market Decisions*, interim deliverable to the National Cooperative Highway Research Program, Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine, May 2016.

[38] Zmud et al., 2016; Anderson et al., 2014.

[39] Michael Sivak and Brandon Schoettle, "Eco-Driving: Strategic, Tactical, and Operational Decisions of the Driver That Influence Vehicle Fuel Economy," *Transport Policy*, Vol. 22, July 2012, pp. 96–99.

[40] Anderson et al., 2014.

decreases in future carbon intensity of electricity, "right sizing" of vehicles, and higher miles traveled per vehicle.[41]

On the other hand, passengers may prefer larger autonomous vehicles to allow them to take better advantage of the opportunity to do things other than driving, resulting in lower fuel economy and greater emissions.[42] And, of course, they may drive more.

The Impacts of Autonomous Vehicles on Land Use

Automobile use has influenced the form and extent of land development in the United States, leading in large part to sprawl (that is, low-density, inefficient land-use patterns).[43] The land allocated to automobile infrastructure poses a cost to society: It could otherwise be used for farms, open space, homes, businesses, and other facilities, with associated environmental, economic, and public health effects.[44]

Autonomous vehicles may affect land use in two opposite ways, and both could take place. Commute time and distance are among the key factors households consider in deciding where to live. While areas father away from central business districts offer many benefits, particularly in housing size and cost, a longer commute may be too costly, both in terms of travel and time costs. However, given the ability to engage in other activities while in an autonomous vehicle, the opportunity cost of transportation declines. This could increase the willingness of households to locate farther away from the urban core, increasing urban sprawl.[45]

On the other hand, autonomous vehicles could also lead to greater density in core urban areas. Driving remains the dominant mode of passenger travel in the United States, even in large cities with good transit options, but the typical automobile is parked for about 95 percent of its lifetime.[46] As of a decade ago, the total area devoted to parking spaces in major central business districts was, on average, about 31 percent of the district area.[47] The emergence of autonomous vehicles could sharply reduce the amount of parking needed in core urban areas in several ways. First, after dropping off its passenger or passengers in a downtown location, an autonomous vehicle could pilot itself to a remote lot in a peripheral area, reducing the amount of parking needed in the densest urban areas where land values are highest. Second, as described earlier, autonomous vehicle technology might lead to a new model for urban mobility in the form of driverless taxis. Under such a system, autonomous vehicles would not need to park after every

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[41] Jeffery B. Greenblatt and Samveg Saxena, "Autonomous Taxis Could Greatly Reduce Greenhouse-Gas Emissions of US Light-Duty Vehicles," *Nature Climate Change*, Vol. 5, No. 9, 2015, pp. 860–863.

[42] Anderson et al., 2014.

[43] Robert Burchell, George Lowenstein, William R. Dolphin, Catherine C. Galley, Anthony Downs, Samuel Seskin Katherine Gray Still, and Terry Moore, *Costs of Sprawl-2000 TRCP Report 74*, Federal Transit Administration, 2002.

[44] M. A. Delucchi and J. J. Murphy, "How Large Are Tax Subsidies to Motor-Vehicle Users in the US?" *Transport Policy*, Vol. 15, 2008, pp. 196–208.

[45] Anderson et al., 2014.

[46] Donald C. Shoup, *The High Cost of Free Parking*, Chicago: Planner's Press, 2005.

[47] Shoup, 2005.

trip; rather, after dropping off one passenger, they would simply travel to pick up the next passenger. Third, the convenience and low cost of such a system might induce many urban dwellers to forgo car ownership, or at least to reduce the number of cars owned. Thus, driverless taxis could reduce the number of parking spaces needed in residential buildings, as well as at commercial centers.[48] These effects, emphasizing the service character of transportation, could free up substantial amounts of space in urban areas for other valuable uses: homes, businesses, parks, hospitals, and so on.

Driving Externalities May Prevent the Benefits from Being Realized

While the effects of autonomous vehicles are complex, some outcomes are clear wins. If safe autonomous vehicles are developed and used widely and responsibly, the current public safety crisis in the U.S. transportation system could be mitigated. If safe and usable autonomous vehicles are developed, mobility could increase for millions of Americans who currently have limited mobility. In addition, if the potential increase in transportation demand created by autonomous vehicles were mitigated or decoupled from fossil fuels, there could be enormous energy security, public health, and environmental benefits. Related to this, if shared autonomous vehicles are widely available and widely used, this could reduce private vehicle ownership and the need for road infrastructure, allowing repurposing of land to more economically productive uses.[49]

Yet these outcomes may not actually be realized because many benefits accrue to society rather than to either the producers or consumers of autonomous vehicles. Consumers may be unwilling to pay for expensive technology if much of the benefits go to others, and consequently, producers may be less willing to develop them. Thus, there is less incentive for producers and consumers to take actions that would achieve beneficial outcomes.[50]

Safety is a good example of this phenomenon, with significant consequences for autonomous vehicles. When an individual drives unsafely or operates an unsafe vehicle, he not only puts his own well-being at risk but also the well-being of all other road users around him, including pedestrians and bicyclists. However, in our current transportation and legal system, an individual is responsible for only a fraction of the full cost of being unsafe. In many states, motorists are required to carry only $30,000 (or less) worth of liability insurance—far less than is necessary to compensate someone for a serious injury, much less a loss of life. This leaves a huge gap between the harms that are regularly inflicted by drivers and the amount available for legal recovery. In essence, society subsidizes dangerous vehicles and driving behavior, creating less incentive for safer vehicles and behaviors.

Economists call this an *externality*. An externality is an effect that one party imposes on another party without compensating them for the effect if it is negative or charging them for it if

[48] Zmud et al., 2016.

[49] Zmud et al., 2016.

[50] Zmud et al., 2016.

it is positive.[51] The free market does not allocate resources well in the presence of externalities because the true costs and benefits of actions are distorted.

Consider how the safety externality dampens the market for safe vehicles, including safe autonomous vehicles. First, buyers' incentive to purchase safe autonomous vehicles (which we can expect to be expensive, at least at first) is less than it would be if full social benefits of safe vehicles were reflected in a lower price tag. Second, and related, auto manufactures' incentives to create as-safe-as-possible autonomous vehicles are less than they should be, because safety is undervalued in the marketplace.[52] The result is that very safe autonomous vehicles could be technologically feasible, but fewer firms will develop them and fewer individuals will buy them because many of their benefits accrue to the public rather than the purchaser.

Safety is just one externality. Many of the benefits and the costs of autonomous vehicles (and vehicles in general) are external. If a buyer's car is energy efficient, it helps the buyer somewhat, but most of the benefits go to other people (e.g., the people who breathe the air in the area where that vehicle is driven). Those costs (e.g., of poor air quality) are real and are borne by society. If the benefits of reducing pollution are not factored into the buyer's cost of the vehicle, there is little incentive for them to buy it, particularly if the vehicle is more expensive than less-efficient alternatives.

Policymakers Can Promote Beneficial Outcomes by Internalizing Externalities

So, how can we solve the externality problem? The key is to use policy tools to "internalize" externalities so that market prices reflect the true costs and benefits of private-sector actions. This can be done with subsidies, user fees, mandates, and privileges to ensure that producers and consumers of autonomous vehicles receive the benefit from (and are thus incentivized toward) making choices that benefit society.

As just one example, when a driver uses a busy road, he adds to congestion that other travelers experience, but he does not have to pay for the cost of that extra congestion—the lost productivity of others as they sit in traffic, the delay in goods movement, and the local increase in pollution. But congestion is a problem that could be solved. Nearly all passenger vehicles in this country have space for at least four people, but on average, there are just 1.67 passengers.[53] Those unused seats are extra, already-built transportation capacity. But that capacity is not used because, in large part, the costs of carpooling are internal (the driver bears the cost of the effort and hassle) but the benefits of carpooling remain external (the driver does not benefit from reducing society's congestion). High-occupancy-vehicle (HOV) lanes are one partial remedy: They help internalize the positive externalities of carpooling by enabling carpoolers to themselves bypass congestion and get to their destinations faster.

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[51] James M. Buchanan and Wm. Craig Stubblewine, "Externality," *Economica*, Vol. 29, No. 116, 1962, pp. 371–84.

[52] This externality explains, in part, why there is little market for vehicles that are designed to better protect individuals outside of the vehicle in the event of a crash. The technology exists, but the societal benefit of protecting others does not reach the buyer in the form of a relatively lower-priced vehicle.

[53] Federal Highway Administration, *Summary of Travel Trends: 2009 National Household Travel Survey*, June 2011. As of November 8, 2016:
http://nhts.ornl.gov/2009/pub/stt.pdf

There are many policy options to internalize not only the congestion externality but also the other driving externalities related to safety, pollution, oil dependence, and mobility. These include creating insurance requirements that strengthen the market for road safety, offering transit incentives that reduce congestion, and offering rebates for using fuel-efficient vehicles, among others. Each option has a long history of research and discussion, and these and other options have been implemented to varying degrees.

It is not possible today to give each policy the discussion it warrants. Nevertheless, now is the time to revisit the impact of driving externalities and the policies to internalize them, because autonomous vehicles *could* improve our transportation system tremendously, *provided the right market signals are in place*. In other words, because so many of the benefits and costs of autonomous vehicles would accrue to people other than the buyer, internalizing externalities is a key step to ensuring that society minimizes their disadvantages and maximizes their benefits.

There is also a current window of opportunity to send those new market signals because consumer expectations about autonomous vehicle costs, performance, and other characteristics are not yet set. For instance, congestion pricing requires drivers to pay a fee to travel during peak rush hour, because driving during rush hour imposes higher congestion costs on everyone than driving at other times does. Although congestion pricing is widely recognized as an effective means of internalizing the cost of congestion and thereby reducing congestion, it has been difficult to implement, partly because drivers are unaccustomed to paying different prices based on when they travel. However, today, many private ride-sharing companies charge an extra fee for their services during rush hour, analogous to congestion pricing. Because these services are new and the reasons for the charge are understandable to consumers (greater demand for a limited supply of goods), these fees have been generally acceptable. Similarly, consumers may be more amenable to new policies that internalize the externalities of driving now, before autonomous vehicles are available, rather than later, once expectations about autonomous vehicles are set. Of course, these policies must apply to all auto travel, not just autonomous vehicle travel, for the market signals to be clear.

In sum, it is not possible to fully predict what a future with autonomous vehicles will look like. However, by using the current window of opportunity to internalize the externalities of driving, it is possible to send the right market signals, paving the way for a future transportation system that maximizes the potential advantages while minimizing the potential disadvantages. This is an exciting future of increased mobility and economic growth and greater transportation safety, efficiency, equity, and sustainability.

Conflict of Interest Statement: Nidhi Kalra's spouse, David Ferguson, is co-founder and president of Nuro, an autonomous vehicle startup. He previously served as a principal engineer for Google's driverless car project. This written testimony was carefully reviewed by subject-matter experts within the RAND Corporation; the research quality assurance team for the RAND Justice, Infrastructure, and Environment division; and the RAND Office of Congressional Relations. However, the opinions and conclusions expressed in this testimony are the author's alone and should not be interpreted as representing those of the RAND Corporation or any of the sponsors of its research.