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Featured Article

The Future of Autonomous Vehicles: Lessons from the Literature on Technology Adoption

Scott Kaplan*, Ben Gordon, Feras El Zarwi, Joan L. Walker, and David Zilberman

Scott Kaplan and David Zilberman are with the Department of Agricultural and Resource Economics, UC Berkeley. Ben Gordon is with the Nonprofit Finance Fund, Los Angeles, CA. Feras El Zarwi is with Uber, San Francisco, CA. Joan L. Walker is with the Department of Civil and Environmental Engineering, UC Berkeley. The authors thank the University of California Center on Economic Competitiveness in Transportation for funding supporting this project.
*Correspondence may be sent to: scottkaplan@berkeley.edu.

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Abstract *The introduction and adoption of autonomous vehicles (AVs) will likely reshape the transportation system and many economic activities. The economic literature on technology adoption, based on studies in agriculture and other sectors, provides lessons on the diffusion of AVs and its social and economic impacts. We rely on the threshold model of diffusion, where heterogeneous agents make decisions pursuing their self-interests. Applications of the threshold model point to case studies of other technologies where one can gain information and make predictions about the future of AVs. We find that private ownership of AVs may prevail after a transition period, as was the case in other technologies like computers, tractors, and conventional vehicles. With technological progress, the cost of privately owning AVs may decline. Further, there will be an increase in vehicle miles traveled (VMT) per capita, there may be more vehicles on the road, and perhaps the transportation user-base will expand to include those currently facing limited mobility. Congestion is likely to depend on the tradeoff between the expansion of VMT and increased efficiency of AVs to communicate and help regulate traffic. Furthermore, differentiation of vehicles will increase as driving time becomes freed for other activities. These trends may lead to increased greenhouse gas emissions and expansion of the transportation sector. Finally, the technology will evolve and may result in complementary innovations needing to be addressed, including the "last 10 feet" problem. It is evident that the future of the transportation system governed by AVs is most likely not going to be sustainable. This necessitates the importance of developing and enforcing rigorous policies at the metropolitan level and TNC levels to ensure a sustainable evolution of the future of transportation mobility.*

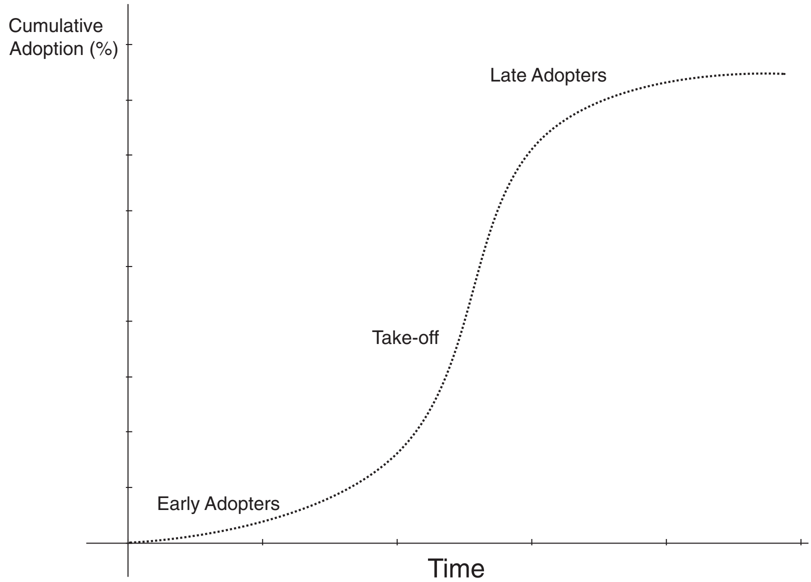
Key words: Autonomous Vehicles, Technology Adoption, Diffusion, Private Ownership, Sharing.

JEL codes: O33, R40.

Recent advances in global positioning systems (GPS), light detection and ranging (LIDAR), radar, and machine learning have made autonomous vehicles (AV), which drive themselves, technically feasible. Level 5 AVs, which are cars that drive without a human backup, were first tested in an urban setting in 2007, and are expected to be commercially available by 2020–2030 (Caddy 2015; Stoll 2016). These AVs are being promoted as a mechanism to increase transportation safety and improve human welfare (Fagnant and Kockelman 2015). Last year, there was an estimated $300 billion in economic losses associated with congestion and accidents alone, and close to 36,000 fatalities from vehicle crashes (Cambridge Systematics 2011). The evolution of AVs is rapid, but the level of autonomy itself is gradual, and the degree of reliability and safety is evolving alongside of it. The level of autonomy has proven to be an important factor for consumers: there still exists significant consumer resistance to full vehicle automation (Kockelman et al. 2016). This is no different than technological change witnessed in the past, which often encounters social, institutional, and political resistance (Mokyr 2000; Juma 2016). Furthermore, the adoption and diffusion of technologies are often gradual and varied over space and time, reflecting heterogeneity among individuals and learning processes (Rogers 2010).

The rich literature on technology adoption provides insights on the process of adoption, the ecosystem of a technology, and issues of acceptance and regulation. This paper relies on the economic literature covering technology adoption and diffusion—which initially studied agricultural technologies—to assess the impact of autonomous vehicles (AVs) on transportation consumers, the automobile industry, vehicle use patterns, the environment, and policies. Technology diffusion is an aggregate adoption process that can be understood through analyzing the heterogeneous characteristics of individuals and organizations affected by AVs, as well as infrastructure and institutions that complement and regulate them. The analysis below shows that although AVs may be seen as a means to reduce dependence on the personal car, the literature on technology adoption suggests that it will actually enhance the range of functions performed by a vehicle, especially personal vehicles. This suggests that in the long run, as prices of AVs decrease, there may be increased private vehicle ownership rates, and even an increase in total number of cars per capita. These results contradict much of the current literature on the private ownership versus sharing debate with respect to AVs, including Firnkorn and Müller (2015), Walker and Johnson (2016), Arbib and Seba (2017), and Litman (2014). In addition, AVs will likely increase vehicle miles traveled (VMT) per capita and greenhouse gas (GHG) emissions. The impact of AVs on congestion is not clear—congestion will increase with additional VMT, but new and more efficient driving algorithms will tend to reduce it. How impactful this technology will end up being depends on random events (e.g., accidents), overcoming political and social resistance, and harmonizing regulatory frameworks and infrastructure. The first section of this paper presents an integrated framework of technology adoption that incorporates heterogeneity and dynamic considerations to individual decision-making. Next, we address several implications for how AV will impact the automobile industry and transportation sector. We finish with a discussion of these findings and relate them to future work in this field.

Figure 1 S-shaped diffusion curve



Basic Economics of Adoption of AVs

This section presents the main lessons from the economic literature on technology adoption and diffusion, and its general application to the case of AVs. Adoption is a decision by an individual to use a new technology, while diffusion refers to aggregate adoption and is measured by the percentage of adopters in a target population. It is useful to distinguish between indivisible (owning a car) and divisible technologies (share of travel by public transportation; Feder et al. 1985).

The fundamental finding on diffusion of a technology, measured by share of adopters in each period, is that it takes an S-shaped function of time (see figure 1). Rogers (2010) explains the S-shape as a process of imitation, where trendsetters adopt a technology initially, and then others follow. However, the imitation model does not explain how self-interest and differences among individuals affect adoption. Our analysis is based on the threshold model, which provides an expanded approach to adoption. Individuals learn about technologies from trendsetters, but then make the decision about whether to adopt themselves. The threshold model allows us to estimate parameters of diffusion and design policies for the introduction of new technologies.

The threshold model was introduced in David (1969) and consists of three elements: individual decision-making, heterogeneity, and dynamics. The individual decision-maker (a consumer or a firm) is assumed to pursue self-interest subject to constraints over knowledge about product availability and performance. In the case of transportation, there are three user segments: consumers, transportation network companies (TNCs), and other companies. Consumers try to maximize utility from travel and other consumption goods, subject to constraints. The utility from travel depends not only on getting from one location to another, but also convenience, reliability, and pride of ownership, while the constraints include budget, physical constraints (i.e., ability to drive), and legal constraints. Adoption of AVs will increase as their price decreases relative to conventional vehicles and their amenities improve. Using AVs appeals to consumers—it allows one to perform other tasks during transportation, which is especially valuable for consumers with a high opportunity cost of time. AVs will reduce operational costs for TNCs because of reduced labor costs, and thus reduce the cost of shared vehicles for consumers. Similarly, freight and retail businesses will benefit from AVs because they reduce labor costs and enhance delivery efficiency. Once the cost savings (net benefits) from AVs is greater than the difference in cost between AVs and conventional vehicles, firms will invest in them.

Adopters vary due to heterogeneity in human capital, income, education, preferences, reliance on others, etc. Some agents are early adopters ("innovators" according to Bass 1969), while others are "followers" and "laggards." In the case of AVs, wealthier individuals are likely to be early adopters of private AVs and poorer individuals may use TNCs. Individuals with limited mobility or driving capacity are also likely to be early adopters. Similarly, early adopters will likely include firms with high levels of VMT, including the freight industry, and the rental car sector (Zmud 2017). Spatial heterogeneity is another important factor that will affect AV adoption—lower transportation density areas further from business districts are more likely to purchase AVs, while individuals in dense urban areas are more likely to use TNCs.

While several factors affect a specific agent's decision of whether or not to adopt, diffusion is affected by dynamic processes, including learning about the technology through learning-by-doing (reducing the cost of production) or learning by using (improving utilization) and network externalities (benefits of using the technology increase with number of users), each of which expand the range of adopters over time (Arbib and Seba 2017). Demand for AVs is likely to increase as the general population ages and average income level increases. Richer individuals are likely to purchase new models and lower-income individuals may adopt AVs through the used car market. Producers (car manufacturers and technology companies) will invest in the technology and supply it. With learning-by-doing, they will enhance quality and differentiate their product.

Finally, political considerations affect the diffusion of modern technologies through policies and regulation. Countries, regions, and interest groups that benefit from a technology are more likely to develop frameworks that support it (Rausser, Swinnen, and Zusman 2011). Risk considerations and random events in other related sectors might also affect the dynamics of technology adoption. For example, the Three Mile Island accident slowed the diffusion of nuclear power technologies (Slovic, Flynn, and Layman 1991). Given that there are large segments of consumers who oppose the technology, as well as the presence of powerful interest groups in the transportation sector, AVs are likely to face substantial regulatory debate and delays in commercialization.

Major Implications of Introduction of AVs

The literature on technology adoption and diffusion as well as the analysis in the previous section suggests several predictions about the patterns of diffusion of AVs over time.

PROPOSITION 1: *Private ownership of AVs is likely to prevail in the long run.*

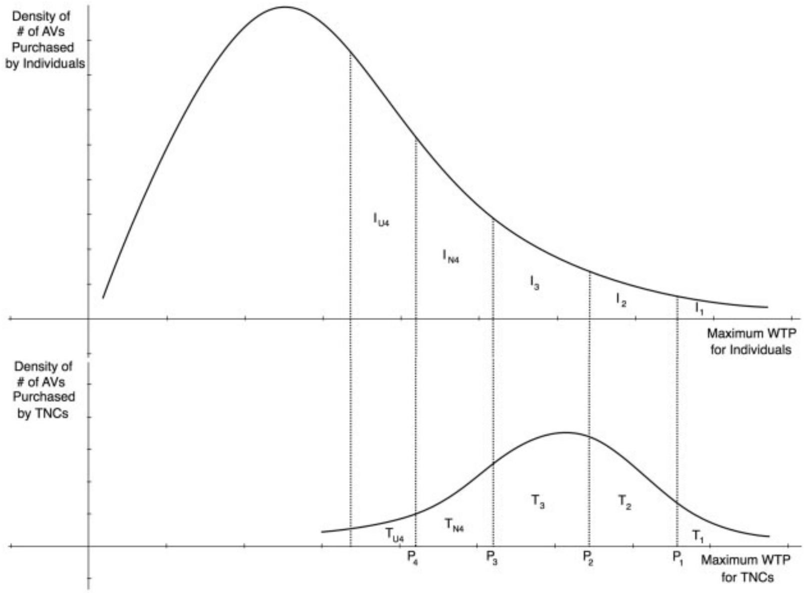
In the long run, private ownership of AVs will prevail. While in the short run we do acknowledge that there may be a shift towards sharing that is a result of the cost differential between owning a new AV versus sharing an AV, we expect that individuals will gradually move towards owning their own AVs. Some papers, including Firnkorn and Müller (2015), Walker and Johnson (2016), Arbib and Seba (2017), and Litman (2014) suggest that the introduction of AVs will mostly take place through the shared economy and reduce the proportion of private vehicle ownership. For example, Arbib and Seba (2017) suggest that by 2030, 95% of all passenger miles traveled in the United States will be through a shared AV. Moreover, Feigon and Murphy (2016) argue that the reduced cost of transportation associated with the introduction of TNCs has already led to reductions in the private ownership of vehicles, and that AVs will reduce costs of using TNCs even further.

Yet our analysis suggests a different outcome for AVs, particularly in the long run. First, the reduction in private transportation in response to the introduction of TNCs suggests that consumers respond to financial incentives, and benefit from different modes of transportation. Still, the reduction in private car ownership has been minor, and in the short run AVs will continue to reduce private ownership. However, the relative cost of AVs will decline over time, and may provide new opportunities to customize cars to meet specific individual needs. Customization of a personal AV will allow drivers to better utilize transport time, and the value of these gains will likely outweigh the cost-savings of TNCs. The same forces that lead individuals to pay to own personalized homes and vehicles today will prevail in the future.

Applying the threshold model directly supports the argument that private ownership of AVs will prevail in the long run. The threshold model suggests that car manufacturers aim to maximize profit by selling as many cars as possible to meet diverse demands, and utility-seeking consumers vary in their additional willingness to pay (WTP) for the convenience, pride of ownership, and customization of private vehicles. Since each private AV serves fewer individuals than a TNC-owned AV, car manufacturers will introduce more designs in order to appeal to individual customers. The diffusion process itself is dynamic, and potential buyers vary in their WTP for new AVs. With learning-by-doing, which will reduce production costs and improve product quality, these cars will be more attractive to more demographic groups. Thus, after an initial period of adjustment, a majority of families in developed countries will have their own AV. Private ownership of AVs may not be as widespread as ownership rates of cars today, especially as the relative cost of alternative transportation is declining, but the basic forces that have led to widespread private ownership of cars will prevail.

Figure 2 presents a graphical illustration of the diffusion process under the threshold model for a simple case where there is one type of AV and its price declines over time (based on Sunding and Zilberman 2001). For clarity, we separate between the market of individual-car purchases and TNC-car purchases (both individuals and TNCs may buy more than one AV), and depict the individual market above the TNC market. The X-axis in both markets is the WTP, which is the maximum amount a potential buyer is ready to spend to own an AV in the presence of all other options (e.g., using ride-sharing, public transit, etc.). The Y-axis represents the probability density of

Figure 2 Diffusion process of AVs for individuals and TNCs



cars purchased by the two different populations under each maximum WTP level.[1] We assume there are a larger number of cars purchased in the individual population than the TNC population. However, the TNC distribution is centered much further to the right, representing a higher average WTP. The areas under the probability density functions represent the total cars purchased by each population. These curves are unimodal, and we assume that the distribution of the cars purchased in the population of individuals is right-skewed, while the distribution of the cars purchased by TNCs is close to normal.

In the first period, the price of the new AV is P_1 and the purchasing group I_1 is comprised mostly of wealthy individuals who have the highest willingness to pay, while group T_1 are the TNC companies with relatively high WTP. The total number of AV purchases at this time is the sum of these two groups. The individuals and TNCs that make up these groups will be the early adopters of the limited quantity of the available AVs. The cost of production will decline through learning-by-doing, and the AV supply will increase as manufacturers seek to diversify their offerings to attract new customers. In the second period, the price declines to P_2, which attracts lower WTP individuals and TNCs. Generally, we expect that $I_2 > I_1$ because it is reasonable to assume that most of the AVs purchased would not be purchased at the highest price. The total number of owned cars after the second period is $I_1 + I_2 + T_1 + T_2$. This process will continue over time as the price falls and under the assumption that each year the exact same AV model is produced. Prices of new AVs will decline from P_3 to P_4 and below, the number of new AVs will increase, and most of the new purchases will be made

[1]*The distribution of willingness-to-pay (WTP) is different than demand because at each maximum WTP level, the vertical axis represents the exact number of additional vehicles that individuals or TNCs will purchase if the price declines incrementally.*

by individuals under these lower prices, as we assume there are more individual buyers than TNC buyers in these areas of the distribution.

Assume that owners of new AVs replace them after three periods. In the fourth period, all AVs purchased in period 1 will be sold in the used market at a market-clearing price that will be lower than P_4. Assuming that individuals with higher WTP are more willing to pay for a new car versus a used car, there will be a group of individual-car purchases I_{N4} that will consist of new AVs in period 4 at price P_4, and another group of individual-car purchases I_{U4} that will consist of used AVs at a price that will be below P_4. This price will be equal to the lowest WTP of all individual-car purchasers in group I_{U4} for a used car (which is WTP for a new car minus some new car premium).[2] It is important to note that figure 2 and the accompanying description represent a simplified analysis; in reality, manufacturers introduce improved and differentiated models that lead the average car to go through the hands of several owners, expanding the number of owners of AVs and the number of AVs on the road. If the number of AVs introduced in each year is greater than the growth in the purchasing population, then the share of AVs per capita is increasing over time, and with it private ownership.

These results are consistent with the experience of other technologies, for example tractors, automobiles, and combines (Olmstead and Rhode 2001), as well as computers (Fichman 1992). Initially, the high cost of harvesting equipment like combines led to the emergence of enterprises that provided equipment and labor was tailored to the needs of individual farmers. Over time, equipment costs fell, scale of operation increased, and a much larger share of farmers owned equipment. The speed of reduction in prices may vary among product categories, but learning-by-doing is consistent nevertheless. In the case of spraying machinery for chemicals in agriculture, as well as other indivisible technologies, most farmers initially rented equipment, but over time as prices decreased and utility of ownership increased, they tended to own the technology outright (Lu, Reardon, and Zilberman 2016). With respect to the emergence of a used AV car market, we examine the case of automobiles today, namely that richer individuals will replace leased AVs every few years, providing a supply of used vehicles. An additional appeal for a privately-owned AV is that it can be customized to serve as an office or home, and will create additional demand relative to automobiles today. Consistent with current patterns, reliance on shared services will continue in public transportation-dense areas, and private ownership will dominate in suburbs and regions underserved by public transportation or TNCs.

The results are also consistent with the analysis of Wadud (2017), which suggests that commercial operators have the most to gain from AVs, and thus will be early adopters. The analysis also recognizes heterogeneity among consumers, and suggests that the wealthiest will be early adopters as well. The survey results analyzed in Daziano, Sarrias, and Sarrias (2017) also find significant heterogeneity in WTP for automation, with more than 10% of respondents stating a willingness-to-pay more than $10,000.

[2]*We do not compute this premium, but assume it is the result of the market-clearing relationship in the used car market where the supply of used cars is exhausted. We do not display it in figure 2, but do indicate the number of individuals that purchase used cars under this price.*

PROPOSITION 2: *Personal-miles traveled, vehicle miles traveled, and vehicle miles traveled per capita will increase.*

Overall personal-miles traveled (PMT), vehicle-miles traveled (VMT), and VMT per capita will increase, as suggested by current AV literature (e.g., Fagnant and Kockelman 2015; Arbib and Seba 2017). We can distinguish between intensive and extensive margin effects of the increase in PMT. On the intensive margin, the opportunity cost of travel time will decline, and with 250 million hours spent in cars annually in the United States (Bigelow 2017), individuals may spend more time engaged in other activities while in transit (e.g., working, resting, or recreating). On the extensive margin, more users (i.e., elderly individuals and children) will have access to use vehicles independently, estimated at an additional 30 million people (Bigelow 2017). Harper et al. (2016) estimate a 14% potential increase in overall VMT as a result of the introduction of AVs and the services provided to non-driving, senior, and disabled populations. These results are consistent with the analysis of Truong et al. (2017) on the impact of AVs. Another extensive margin impact will be the introduction of "zero occupancy vehicles", which increase VMT, and is consistent with the simulation in de Almeida Correia and van Arem (2016).[3]

The literature on adoption of both computers and tractors also finds that reduction in cost has led to strong extensive and intensive margin effects. As the cost of utilizing tractors declined, more people adopted them and they were assigned a larger number of applications, and as computers became more user-friendly, more applications became available and individuals spent more time using them (Fichman 1992; Olmstead and Rhode 2001). An indirect effect of the reduced opportunity cost of transportation time may be enhanced urban sprawl, which will increase the likelihood of individuals living further from central business districts, and as a result their PMT (Anderson and Larco 2017).

One factor that may increase the opportunity cost of travel time is increased congestion. On the surface, more VMT may lead to more congestion, but communication between AVs allows for more vehicles on the road, which reduces the impact on congestion (Litman 2014). The study by Wu, Bayen, and Mehta (2018) suggests that driving algorithms and increased communication between AVs has the ability to stabilize traffic. These authors find that even with a percentage of AVs as low as 6%, there is potential to reduce congestion significantly. Thus, if the reduction in congestion because of improved communication is greater than the effect from additional VMT, then the introduction of AVs may reduce overall congestion, which will further reduce the cost of travel.

PROPOSITION 3: *The overall number of vehicles per capita will increase if the gains from customized vehicles, the increased range of uses, and lower transport costs (including an income effect resulting in more transportation consumers) are greater than the reduction in cost of shared services.*

This is similar to the increased customization and user-friendliness of computers (Fichman 1992). For example, if individuals who do not drive today

[3] *These may be vehicles distributing goods to customers, warehouses, etc., in which the vehicle has only goods but no people. Another example might be a vehicle driving itself to, say, find parking, receive maintenance, or relocate.*

(e.g., the elderly, young, disabled, etc.) prefer to own private AVs, it will contribute towards increasing the number of AVs compared to the present. Another important consideration is intra-household sharing dynamics. The number of AVs per capita will decline if families decide to reduce the number of vehicles they own since the vehicles can drive themselves back to the house to serve another household member. But this factor may be outweighed by the extensive margin effect of AVs, namely the introduction of new uses and users. Similarly, the number of vehicles owned or contracted by firms will increase if the increase in total use of a firm's fleet of cars (measured by miles) is greater than the intensity of use of each AV compared to a traditional vehicle (in terms of miles/car). Thus, while Proposition 2 states that more miles will be traveled, Proposition 3 identifies conditions under which more or less AVs will be on the road.

PROPOSITION 4: *AVs will increase automobile product differentiation and expand the sector.*

AVs will increase product differentiation in the automobile sector, and expand the industry. The economics of recreation (Tribe 2015) suggests that increased time allocated to leisure leads to the introduction and expansion of activities and goods. Because AVs free drivers to conduct other activities, the design of the car may change to allow individuals to utilize their time in other ways. Expanded features and uses of vehicles in terms of driving, safety, and convenience will introduce new players into the transportation sector. We may see the emergence of firms that provide specialized vehicles (e.g., recreation, delivery services, and even living accommodations). AVs may allow individuals with limited mobility to use private transport. However, this will give rise to the "last 10 feet problem", which will result in complementary industries (e.g., services and robotics) that allow these individuals to move from the car to their destination.

PROPOSITION 5: *The impact of AVs on greenhouse gas emissions depends on the sum of its impact on total VMT, energy use of vehicles per vehicle-mile traveled, and carbon content of fuels.*

As we argue previously, AVs will increase VMT, which on its own contributes to increased greenhouse gas (GHG) emissions. The impact on GHG emissions from energy-use per vehicle-mile traveled is not obvious. On one hand, AVs may be associated with increased energy-efficiency for transportation purposes. On the other hand, increased functionality (e.g., work, entertainment, and living) and coordination across vehicles provided by AVs may lead to increased energy use. With respect to fuel content, AVs will not necessarily be electric, and even if they are, electric cars may rely on dirtier electricity sources (e.g., coal). The ambiguous impact of AVs on GHG emissions is consistent with Fulton, Mason, and Meroux (2017). Greenblatt and Saxena (2015) suggest that the proportion of shared vehicles versus privately-owned vehicles will greatly affect the impact of AVs on GHG emissions. The impact on GHG emissions over time may decline because of learning-by-doing and improvements in efficiency, but increases in VMT and added functionalities may have the opposite effect. Of course, the effect of AVs on GHG emissions will depend on policies, for example a carbon tax, fuel-efficiency standards (e.g., CAFE standards), zoning, or other regulations that affect both VMT and energy efficiency. A complete assessment of the impact of AVs on GHG emissions may require further analysis of its impact on lifestyle, land-use, and time allocation patterns.

PROPOSITION 6: *Introduction of AVs may be delayed due to political and risk considerations, but over time political economic considerations may intensify the adoption of AVs.*

The introduction of AVs to the industrial and transportation sectors may encounter delay due to political economic and risk considerations. For example, freight driver unions and lobbying by taxi companies may slow the introduction of AVs in freight and TNCs. Regions that have a comparative advantage and control over AV technologies are more likely to develop more accepting regulatory frameworks that encourage their adoption. The recent case of genetically modified organisms (GMOs) illustrates this point (Herring and Paarlberg 2016). The technologies were introduced primarily by American companies, and encountered a more favorable regulatory environment in the United States than in Europe, where chemical companies stood to lose from the technologies and farmers had little to gain (Zilberman et al. 2013). Similarly, the introduction of the tomato harvester encountered resistance and objection from farm-workers, and led to reduction in public supported research on mechanization in agriculture (Martin and Olmstead 1985).

While political resistance may slow the introduction of AVs, political pressure over time may lead to public investment in research, communication equipment, networks, and other activities that will benefit the technology. Rausser, Swinnen, and Zusman (2011) argue that farm groups and water suppliers use their political influence to initiate water projects in the United States and elsewhere. Cochrane (1979) argues that settlers and developers use their political clout to expand the railroad system in the United States. Congleton and Bennett (1995) suggest that interest groups and demographic segments that benefit from transportation infrastructure are likely to use the political process to expand this infrastructure.

PROPOSITION 7: *Evolution of AV technology may be slowed by accidents and mishaps.*

The evolution of the technology may be slowed by accidents and mishaps caused by AVs, as well as unexpected events in related industries. Regulatory procedures are responsive to public concern and awareness of risk. For example, food safety regulations were introduced in response to exposure of risks in the meat-packing industry in the early twentieth century (Kolodinsky 2012), and car safety regulations were introduced to reduce the number of car accidents and their impact (Robertson 1996). The introduction of heavy regulations of GM crops in Europe was affected by concerns about food safety in response to Mad Cow Disease (Finucane 2002). Thus, while the technology is very close to being commercially deployable, the legal and regulatory environment needs to “catch up,” which may slow the diffusion of the technology and lead to differences in adoption patterns across locations. Furthermore, there still remain important ethical questions about the decision-making algorithms of AVs when confronted with pedestrians and other conventional vehicles.

PROPOSITION 8: *Introduction of AVs may lead to and benefit from adaptation of infrastructure.*

The introduction of AVs may require the adaptation of transportation systems, and some aspects may get worse before they get better. For example, the co-existence of conventional vehicles with AVs may lead to increased congestion, delays, and possibly accidents during a period of adjustment and learning. This may slow the adoption of the technology, but at the same time, may lead to adaptive investments that will smooth the transition over time. These investments with AVs will allow improved monitoring of and communication between vehicles, and utilize algorithms to improve traffic flow and reduce bottlenecks (Wu, Bayen, and Mehta 2018). Furthermore, de Almeida Correia and van Arem (2016) suggest several adaptation mechanisms to reduce congestion associated with AVs, including creative parking facilities and parking fees. Adaptation to AVs will need to go beyond the transportation system—it may change zoning laws and urban design. These changes may be gradual, and the diffusion of AVs and changes in urban design will coevolve. David's (1975) analysis of the diffusion of the dynamo, engine, and computer suggests that infrastructural constraints and limited capacity to adapt slowed the diffusion of these technologies. However, building infrastructure to accommodate these technologies, for example the highway system and the Internet, accelerated their diffusion later on.

PROPOSITION 9: *Demographic and geographic heterogeneity will result in different regulatory and adoption patterns of AVs.*

Heterogeneity among regions in terms of income and demographic distribution, infrastructure, and city layout will result in differences in regulation and adoption patterns of AVs. Higher-income and high-tech regions may be early adopters of privately-owned AVs. Large metropolitan regions may emphasize the use of AVs through TNCs. But the broad diffusion of the technology across the United States and the world may require harmonization of regulations across regions. The introduction of the regulatory framework will be time-consuming and may affect the rates and patterns of diffusion of AV. Teske, Teske, and Best (1993) suggest that the evolution and diffusion in the United States of railroads, trucking, and other transportation systems, as well as telecommunication systems, were strongly affected by the changing regulatory environment. This suggests that the diffusion of AVs may benefit from the introduction of regulations that reduce transaction costs of new AV systems while allowing for diversity and competition of transportation systems.

PROPOSITION 10: *Introduction of AVs may increase domestic tourism and provide new opportunities for rural areas.*

AVs will reduce the stress and time costs associated with driving, and thus increase the appeal of domestic travel, especially among retired individuals. Furthermore, the economic benefit associated with living further from city centers will increase, which may lead to their expansion. Basic logic from urban economics suggests that reductions in transportation cost increases the relative value of properties further from the city and leads to larger sprawl

(Glaeser and Kahn 2004). Wu, Sexton, and Zilberman (2019) suggest that the rise in energy prices from 2005–2007 resulted in relatively large declines in property values farther from cities, and resulted in many home foreclosures. Transportation costs include both fuel and time—AVs will reduce the time cost of travel. Additionally, AVs will reduce the cost of shipping, as it will eliminate drivers that require time to rest, thus reducing the cost disparity of shipping from more rural areas.

Conclusion

The introduction of AVs will likely reshape the transportation system and economic activity in general. Walker and Johnson (2016) and Sperling (2018) suggest that AVs are expected to reduce the number of cars on the road. This paper suggests otherwise based on the experience of other technologies. There will likely be an increase in miles traveled per capita, more vehicles on the road, increased sprawl, and expansion to include users currently facing limited mobility. Our analysis indicates that private AV ownership will prevail after a transitionary period. The differentiation of vehicles may increase as driving time becomes freed for other activities. These trends may lead to increased GHG emissions from and expansion of the transportation sector. The technology will evolve and may result in complementary innovations to address, including the "last 10 feet" problem.

The dynamics of AV diffusion will depend on technological progress as well as social acceptance and regulatory frameworks. There may be significant differences in adoption patterns across regions and population segments. Diffusion may be delayed by accidents, resistance by groups negatively affected by the technology (freight and taxi drivers), and regulatory gridlocks. Outcomes depend on policy environments both at the micro and macro levels. The policy environment is likely to change as the technology evolves and may affect the dynamics and use of the technology itself. It is evident that the future of the transportation system governed by AVs is most likely not going to be sustainable. This necessitates the importance of developing and enforcing rigorous policies at the metropolitan level and TNC levels to ensure a sustainable evolution of the future of transportation mobility. Further research on the economics of AVs needs to be more quantitative and utilize data as it becomes available. The challenge of research on AVs is not only to develop a better technology, but to develop economic, political, and social insights that will lead to more effective implementation.

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