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7. AUTHOR
Ben Gordon, Scott Kaplan, Feras El Zarwi, Joan Walker, and David Zilberman

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2150 Shattuck Avenue, Suite #300
Berkeley, CA 94704-5940

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

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

Abstract

Introduction and adoption of autonomous vehicles (AVs) will likely reshape the transportation system and many economic activities. The economic literature on technology adoption can provide lessons on the diffusion of AVs as well as the social and economic impacts. We rely on the threshold model of diffusion, where heterogeneous agents make decisions to pursue their self-interests and whose decisions change over time with new technologies and knowledge. We utilize the many applications of the threshold model and point to case studies of other technologies to gain information and make predictions about the future of AVs. Most notably, we find that private ownership of AVs will prevail after a transition period, as was the case in other technologies like computers, tractors, and cars. With technological progress, the cost of privately owning AVs will decline and they will be customized to meet individual tastes. In addition, there will be an increase in vehicle miles traveled per capita, may be more vehicles on the road, and an expansion of the transportation user-base to include those currently facing limited mobility. Furthermore, differentiation of vehicles will increase as driving time becomes freed for other activities. These trends may lead to increased GHG emissions and expansion of the transportation sector. Finally, the technology will evolve and may result in complementary innovations to address, including the 'last 10 feet' problem.

June 2018

Introduction

Autonomous vehicles (AV) are vehicles that drive themselves. Recent advances in GPS, LIDAR, RADAR, and machine learning have made them technically feasible (Urmson 2015). 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 (Stoll 2016; Caddy 2015; Steward 2014). They are being promoted as a mechanism to increase transportation safety and improve human welfare (Fragnant 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 fast, 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 proved to be an important factor for consumers: there still exists significant consumer resistance to full automation of vehicles (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, adoption and diffusion of technologies are often gradual and varied over space and time, reflecting heterogeneity among individuals and learning processes (Rogers 2010).

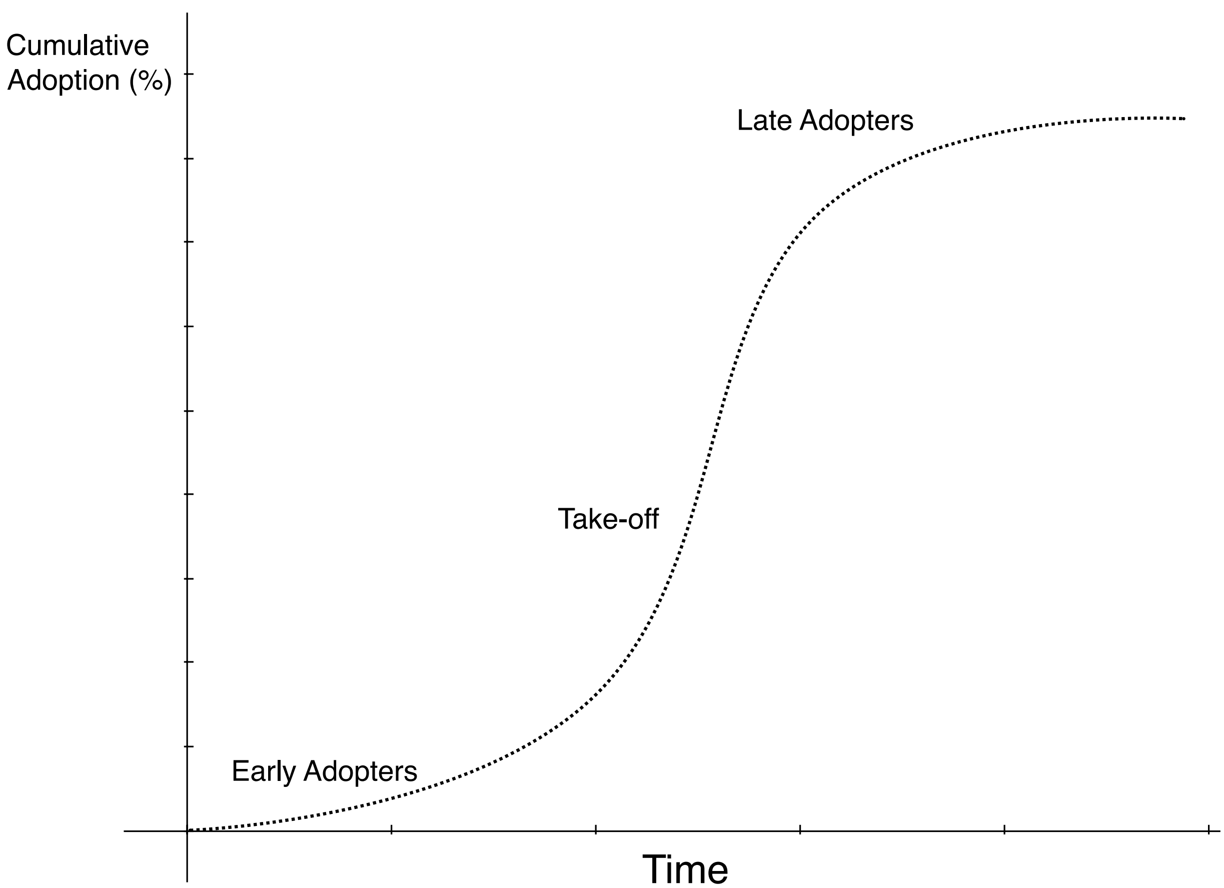
The rich literature on technology adoption provides insight on the process of adoption, the ecosystem of a technology, and issues of acceptance and regulation. This paper relies on the economic literature covering technology adoption and diffusion to assess the impact of autonomous vehicles (AVs) on 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, congestion (at least in the short-run), and greenhouse gas (GHG) emissions. 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.

Basic Economics of Adoption of AVs

In this section, we aim to present 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 is aggregate adoption and is measured by the percentage of adopters in 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 trend-setters 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 trend-setters, but then make the decision about whether to adopt themselves. The threshold model allows us to both estimate parameters of diffusion and to design policies to introduce new technologies.

Figure 1: S-Shaped Diffusion Curve



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 product performance. In the case of transportation, there are three user segments, namely 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 its price decreases relative to conventional vehicles and as amenities improve. Using AVs appeals to consumers as 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 cost 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 saving from AV is greater than the difference in cost between AVs and conventional vehicles, firms will invest in them.

Individuals vary due to heterogeneity in human capital, income, education, preferences, reliance on others, etc. Some individuals 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. Statistical and marketing analysis aims to identify the features of the market segments that are most likely to adopt a technology over time in order to target marketing efforts towards these groups.

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 adoption of modern technologies through policies and regulation. Countries, regions, and interest groups that benefit from technology are more likely to develop frameworks that support it (Rausser, Swinnen and Zusman 2011). Risk considerations and random events in other related sectors may also affect dynamics of technology adoption. For example, the 3-Mile Island accident slowed the diffusion of nuclear power technologies (Slovic 1991).

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

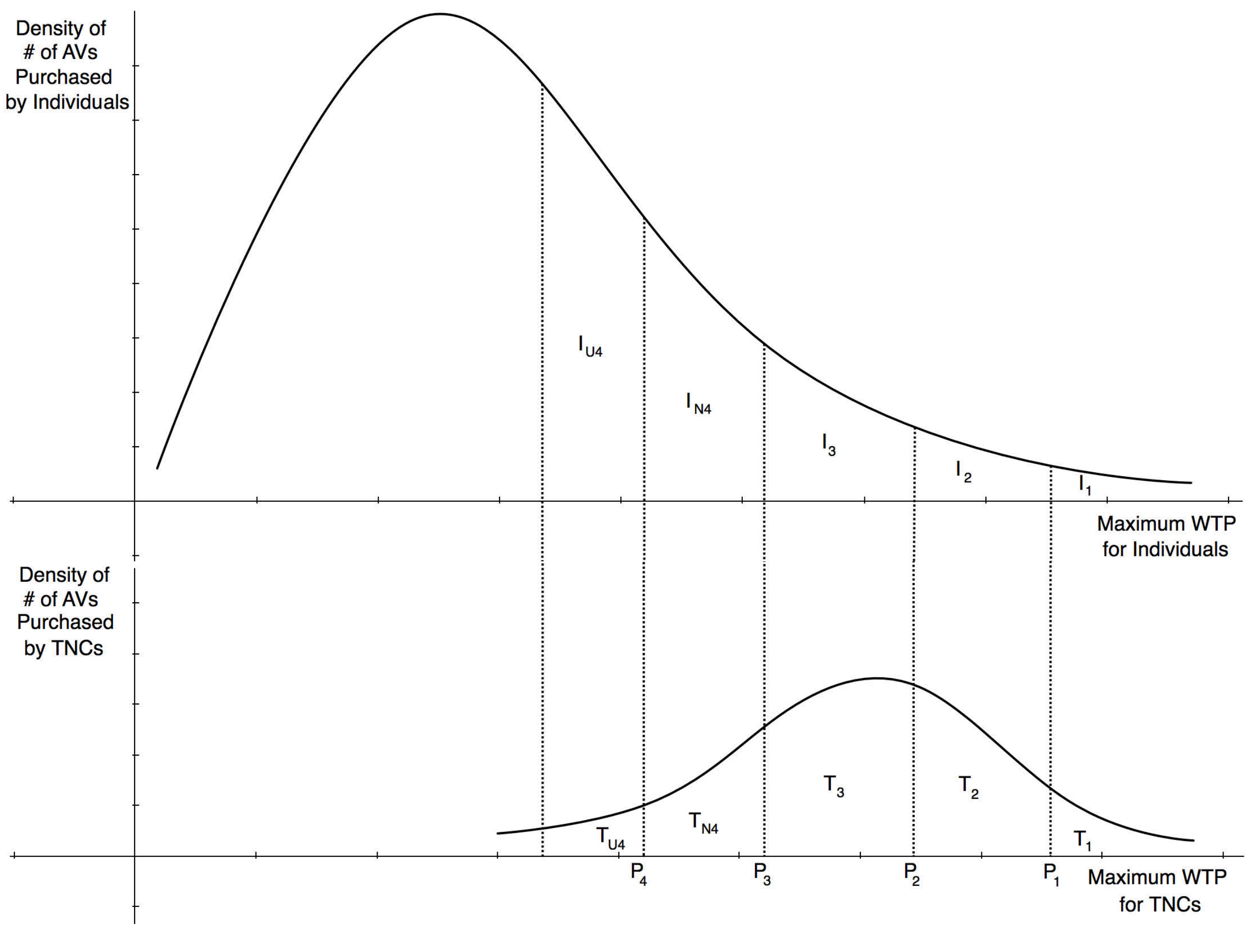
In the long-run, private ownership of AVs will prevail. While in the short-run we do acknowledge that there may be a shift towards sharing that is a result of the cost differential between owning a new AV versus sharing an AV, we expect in the long-run that individuals will move towards owning their own AVs. This result may contradict suggestions by Firnkorn and Müller (2015), Walker and Johnson (2016), Arbib and Seba (2017), and Litman (2014) that 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 U.S. will be through a shared AV. Moreover, Feigon and Murphy (2016) find that introduction of TNCs, and the reduced cost of transportation that it entails, has already led to reductions in private ownership of vehicles, and AVs will reduce costs of using TNCs even further. Yet, our analysis suggests a different outcome.

First, the reduction in private transportation in response to 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. It is also clear that in the short run, AVs will continue to reduce private ownership. However, AVs may provide new opportunities to customize features of cars to provide additional benefits to consumers. The personalized AVs will allow drivers better utilization of 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.

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 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. Diffusion theory suggests that the rate of private ownership of AVs will decline as its relative cost (both economic and non-monetary) to other transportation options increases, and in lower income segments of the population and societies.

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 appears in Figure 2 (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 the 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 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, representing that the share of the individual-car purchasers with higher WTP is declining as WTP increases, while the distribution of the cars purchased by TNCs is close to normal.

Figure 2: Diffusion Process of AVs for Individuals and TNCs



[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 from a slightly higher level.

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

Now, suppose we 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-cars 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).[1] Figure 2 and this 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). The speed of reduction in prices may vary among product categories, but learning by doing is consistent nevertheless. In these cases, firms initially purchased the technology and rented it to users, but as prices fell, individuals purchased the technology outright. This was the case of spraying machinery for chemicals in agriculture as well as other indivisible technologies, where over time individuals tended to adopt as the price decreased and utility of ownership increased (Lu, Reardon, 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

[1] 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.

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 (2016), 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 et al. (2017) also find significant heterogeneity in WTP for automation, with more than 10% of respondents with a stated willingness-to-pay more than $10,000.

Proposition 2: Personal-miles traveled, vehicle miles traveled and vehicle miles traveled per capita will increase

Overall personal-miles traveled (PMTs), vehicle-miles traveled (VMTs) and VMTs per capita will increase, as suggested by current AV literature (e.g. Fragnant and Kockelman 2015; Arbib and Seba 2017). The opportunity cost of travel time will decline, and with 250 million hours spent in cars annually in the US (Bigelow 2017) and thus individuals may spend more time in transit engaged in other activities (e.g. working, resting, recreation, dating). Furthermore, more users (i.e. elderly 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 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. Finally, AVs will lead to "zero occupancy vehicles[2]," which increase VMT, which is consistent with the simulation in de Almeida Correia and van Arem (2016). A similar pattern occurred in the adoption of tractors and computers. As the cost of tractors declined, 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). The expansion of VMTs may increase congestion, which may slow the transition towards AVs. But, as AVs allow for more vehicles on the road, this constraint is relaxed (Litman 2014). Further, one indirect effect that may result is the increase in likelihood of individuals living further from central business districts (Anderson and Larco 2017).

Proposition 3: 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 (e.g. the elderly, young, disabled, etc.) prefer to own private AVs, it will contribute towards increasing the number

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[2] 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.

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 the 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 Two states that more miles will be traveled, Proposition Three 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 both in terms of driving and safety as well as 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: AVs may increase greenhouse gas emissions

AVs may actually increase greenhouse gas (GHG) emissions, depending on the energy-efficiency of the vehicles as well as the carbon content of the sources of energy used to power them. This result is consistent with Fulton, Mason, and Meroux (2017). AVs will likely increase total VMT and may require additional energy for autonomous functions of control that don't exist in cars today, and therefore increase the demand for energy. AVs will not necessarily be electric, and even if they are, electric cars may rely on dirtier electricity sources (e.g. coal). Further, the proportion of shared vehicles versus privately owned vehicles will greatly affect the impact of AVs on GHG emissions (Greenblatt and Saxena 2015). Over time, GHG emissions from transportation may decrease, but even then the decline is likely to be smaller with AVs because they not only increase VMTs, but also the energy-intensity of transport because additional computing power and data storage is required for automation.

Proposition 6: Introduction of AVs may be delayed due to political economic and risk considerations

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 U.S. 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).

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 20th 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 require adaptation of transportation systems

Introduction of AVs may require 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 and delays, and possibly accidents. 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. 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. de Almeida, Correia and van Arem (2016) suggest several adaptation mechanisms to reduce congestion associated with AVs, including creative parking facilities and parking fees. Furthermore, 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.

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 AV use through TNCs. But, the broad diffusion of the technology in the US and globally 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 et al. (1993) suggest that the evolution and diffusion in the US 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 introduction of regulations that reduce transaction costs of new AV systems while allowing for diversity and competition of transportation systems.

Proposition 10: Improvements in communication technology and infrastructural investments may reduce congestion

Improvement of communication technology and networking as well as investment in infrastructure may reduce congestion to overcome the likely increase in vehicles. Walker and Johnson (2016) and others suggest that AVs and shared transportation are expected to reduce the number of cars, which also serve to reduce expenditures on infrastructure. But the political economy of technology adoption suggests that political economy may operate to increase highway capacity. Rausser, Swinnen, and Zusman (2011) argue that farm groups and water suppliers use their political influence to initiate water projects in the U.S. and elsewhere. Cochrane (1979) argues that settlers and developers use their political clout to expand the railroad system in the U.S. 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.

Conclusion

Introduction of AVs will likely reshape the transportation system and economic activities in general. The experience of other technologies suggests several important patterns that may seem counter-intuitive. There will likely be an increase in miles traveled per capita, more vehicles on the road, and expansion to include users currently facing limited mobility. Our analysis indicates that private ownership of AVs will prevail after a transition period. 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 diffusion of AVs 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. Further research on the economics of AVs needs to be more quantitative and utilize data as it becomes available. The challenge of AV research is not only to develop a better technology, but to develop economic, political and social insights that will lead to more effective implementation of the technology.

References

Anderson, Kym, Gordon Rausser, and Johan Swinnen. "Political economy of public policies: insights from distortions to agricultural and food markets." *Journal of Economic Literature* 51, no. 2 (2013): 423-477.

Anderson, Marco and Nico Larco. "Land Use and Transportation Policies." *Sharing, Electrification, and Automation*. *UC Davis Institute of Transportation Studies* (2017).

Arbib, James and Tony Seba. "Rethinking Transportation 2020-2030: The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries." *RethinkX: Disruptions, Implications and Choices* (2017).

Barham, Bradford L., Jean-Paul Chavas, Dylan Fitz, Vanessa Ríos-Salas, and Laura Schechter. "Risk, learning, and technology adoption." *Agricultural Economics* 46, no. 1 (2015): 11-24.

Bass, Frank M. "A new product growth for model consumer durables." *Management science* 15, no. 5 (1969): 215-227.

Bigelow, Pete. "What's the Autonomy Economy? | Feature." *Car and Driver*, 2017, www.caranddriver.com/features/whats-the-autonomy-economy-feature.

Caddy, Becca. "Toyota to launch first driverless car in 2020." *Wired* 8 October 2015

Cambridge Systematics (2011) Crashes vs. Congestion: What's the Cost to Society? Prepared for 12th American Automobile Association.

Cochrane, Willard W. *The development of American agriculture: A historical analysis*. U of Minnesota Press, 1979.

Congleton, Roger D., and Randall W. Bennett. "On the political economy of state highway expenditures: Some evidence of the relative performance of alternative public choice models." *Public choice* 84, no. 1 (1995): 1-24.

David, Paul A. "A contribution to the theory of diffusion." *Memorandum no. 71*. Stanford Center for Research in Economic Growth (1969).

David, Paul A. "Technical choice innovation and economic growth: essays on American and British experience in the nineteenth century." (1975).

David, Paul A. "The dynamo and the computer: an historical perspective on the modern productivity paradox." *The American Economic Review* 80, no. 2 (1990): 355-361.

Daziano, Ricardo A., Mauricio Sarrias, and Benjamin Leard. "Are consumers willing to pay to let cars drive for them? Analyzing response to autonomous vehicles." *Transportation Research Part C: Emerging Technologies* 78 (2017): 150-164.

de Almeida Correia, Gonçalo Homem, and Bart van Arem. "Solving the User Optimum Privately Owned Automated Vehicles Assignment Problem (UO-POAVAP): A model to explore the impacts of self-driving vehicles on urban mobility." *Transportation Research Part B: Methodological* 87 (2016): 64-88.

Fagnant, Daniel J., and Kara Kockelman. "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations." *Transportation Research Part A: Policy and Practice* 77 (2015): 167-181.

Feigon, S. and Murphy, C. [2016] Shared mobility and the transformation of public transit. Washington, District of Columbia, United States of America, TCRP Research Report 188.

Fichman, Robert G. "Information technology diffusion: a review of empirical research." In *ICIS*, pp. 195-206. 1992.

Finucane, Melissa L. "Mad cows, mad corn and mad communities: the role of socio-cultural factors in the perceived risk of genetically-modified food." *Proceedings of the Nutrition Society* 61, no. 1 (2002): 31-37.

Firnkorn, Jörg, and Martin Müller. "Free-floating electric car-sharing fleets in smart cities: The dawning of a post-private car era in urban environments?." *Environmental Science & Policy* 45 (2015): 30-40.

Fulton, Lew, Jacob Mason, and ITDP Dominique Meroux. "Three Revolutions in Urban." *UC Davis Institute for Transportation & Development Policy*, 2017.

Greenblatt, J. B., & Saxena, S. (2015). Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Climate Change*, *5*(9), 860-863.

Harper, Corey D., Chris T. Hendrickson, Sonia Mangones, and Constantine Samaras. "Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions." *Transportation research part C: emerging technologies* 72 (2016): 1-9.

Herring, Ronald, and Robert Paarlberg. "The political economy of biotechnology." *Annual Review of Resource Economics* 8 (2016): 397-416.

Juma, Calestous. *Innovation and its enemies: Why people resist new technologies*. Oxford University Press, 2016.

Kockelman, K., Loftus-Otway, L., Stewart, D., Nichols, A., Wagner, W., Li, J., Boyles, S., Levin, M. and Liu, J., 2016. *Best practices guidebook for preparing Texas for connected and automated vehicles* (No. 0-6849-P1).

Kolodinsky, Jane. "Persistence of health labeling information asymmetry in the United States: Historical perspectives and twenty-first century realities." *Journal of macromarketing* 32, no. 2 (2012): 193-207.

Litman, Todd. "Autonomous vehicle implementation predictions." *Victoria Transport Policy Institute* 28 (2014).

Lu, L., Reardon, T., & Zilberman, D. (2016). Supply chain design and adoption of indivisible technology. *American Journal of Agricultural Economics*, *98*(5), 1419-1431.

Martin, Philip L., and Alan L. Olmstead. "The agricultural mechanization controversy." *Science* 227 (1985): 601-607.

Mokyr, Joel. "Innovation and its enemies: the economic and political roots of technological inertia." *A Not-So-Dismal Science: A Broader View of Economics* (2000): 61-91.

Olmstead, A.L., and P.W. Rhode. 2001. "Reshaping the landscape: the impact and diffusion of the tractor in American agriculture, 1910–1960." *The Journal of Economic History* 61:663–698.

Rausser, Gordon C., Johan Swinnen, and Pinhas Zusman. *Political power and economic policy: Theory, analysis, and empirical applications*. Cambridge University Press, 2011.

Robertson, Leon S. "Reducing death on the road: the effects of minimum safety standards, publicized crash tests, seat belts, and alcohol." *American Journal of Public Health* 86, no. 1 (1996): 31-34.

Rogers, Everett M. *Diffusion of innovations*, 4th edition. Simon and Schuster, 2010.

Seward, J. Mobileye NV Gains: Tesla Motors Inc. to Use Multiple Suppliers for Self-Driving Car. *Benzinga* (8 September 2014).

Slovic, P., Flynn, J. H., & Layman, M. (1991). Perceived risk, trust, and the politics of nuclear waste. *Science*, *254*(5038), 1603.

Stoll, John. "GM Executive Credits Silicon Valley for Accelerating Development of Self-Driving Cars." *Wall St Journal* 10 May 2016

Teske, Paul, Michael Mintrom, and Samuel Best. "Federal preemption and state regulation of transportation and telecommunications." *Publius: The Journal of Federalism* 23, no. 4 (1993): 71-86.

Thaler, Richard H. *Misbehaving: The making of behavioral economics*. WW Norton & Company, 2015.

Tribe, J. (2015). *The economics of recreation, leisure and tourism*. Routledge.

Truong, Long T., Chris De Gruyter, Graham Currie, and Alexa Delbosc. "Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia." *Transportation* 44, no. 6 (2017): 1279-1292.

Wadud, Zia. "Fully automated vehicles: A cost of ownership analysis to inform early adoption." *Transportation Research Part A: Policy and Practice* 101 (2017): 163-176.

Walker, Jonathan, and Charlie Johnson. "Peak Car Ownership: The Market Opportunity of Electric Automated Mobility Services." (2016).

Zilberman, David, Jinhua Zhao, and Amir Heiman. "Adoption versus adaptation, with emphasis on climate change." *Annu. Rev. Resour. Econ.* 4, no. 1 (2012): 27-53.

Zilberman, David, Scott Kaplan, Eunice Kim, Gal Hochman, and Gregory Graff. "Continents divided: Understanding differences between Europe and North America in acceptance of GM crops." *GM crops & food* 4, no. 3 (2013): 202-208.

Zmud, Johanna. "Breakout 1: Market Acceptance and Demand: Data Capture and Analysis Techniques to Examine Behavioral Responses to AVs." *Automated Vehicle Syposium*. July 11-14, 2017. San Francisco, California.