David Bennett

dcb2yd

Introduction

While the environmental impact of passenger vehicles has been steadily decreasing in recent decades, passenger vehicles still produce 27% of the greenhouse gas emissions in the United States (EPA, 2017). Additionally, while the US has 30% of the world's cars, it produces half of the world's emissions from cars. Despite the improving emissions standards in this country, more drastic change is required to slow and reverse the transportation industry's contribution to environmental degradation. One promising technological development which could contribute to this reversal is the introduction and adoption of autonomous vehicle (AV) technology to the personal transportation industry. As it stands currently, AV technology has considerable, if unrealized, potential to alleviate many of the issues which currently plague conventional combustion-based personal vehicles.

Before considering the link between autonomous vehicles and sustainability, it is necessary to examine the factors which have caused research, demand, and public interest around autonomous vehicles to expand so rapidly over the last decade. In the current human-dominated driving regime, automobile accidents kill over 32,000 people and injure another 2.3 million in the United States, costing a total of $242 billion annually (NHTSA, 2012), with driver error being the critical reason for 94% of crashes (NHTSA, 2015). With such a large economic cost attributable directly to human error, it follows that there is an industry-wide effort to remove the human element of driving and reduce the overall cost of driving both in human lives and monetarily.

Another significant drawback to traveling by human-driven car is the prevalence of traffic congestion, especially in and around major cities. Considering that 25% of all traffic congestion is caused by vehicle crashes (FHWA 2017), the accident reduction benefits afforded by fully functional AVs will already provide a substantial reduction in the amount of traffic congestion in the US. Beyond lowering the rate of accidents, AVs, by utilizing vehicle-to-vehicle and vehicle-to-infrastructure communication, will reduce and smooth traffic through platooning, smoother acceleration and deceleration, and more efficient route choices (Fagnant 2015). Beyond simple convenience, reducing traffic would almost certainly reduce the aggregate amount of emissions from transport, which in turn would improve air quality, as traffic congestion has been found to have a positive relationship with per-vehicle emissions (Zhang, 2013).

Finally, the characteristic of current vehicles that will be the primary focus of this paper is their environmental impact. Based upon factors such as the synergy between AVs and electrification, as well as the superior efficiency of AVs accelerating and decelerating, and the likely introduction of V2V and V2I communications to self-driving vehicles in the future, it is likely that the growth of utilization of AVs will coincide with a reduction in adverse environmental impacts due to transportation. The bulk of this paper will be dedicated to evaluating relevant research and data on the relationship between autonomous driving and vehicle sustainability in order to establish a concrete relationship between autonomous vehicle technology and environmental sustainability.

Theoretical Framework

As the continuing development and adoption of self-driving vehicle technology involves the interplay of numerous, varied, and at times opposing stakeholder groups, this paper will study autonomous vehicles through the lens of social construction of technology (SCOT). From the perspective of environmental sustainability, the relevant parties to the continuing development of AV technology include environmental activists, automobile manufacturers (with Tesla being the most significant in the space), the U.S. congress, municipal and state governments, potential consumers of electric vehicles, potential consumers of autonomous vehicles, and oil and gas companies. The groups of potential consumers can be further broken down between those who are concerned about the environmental impact of the vehicles they own and those who are not. Important artifacts in this system include computer vision algorithms, decision-making artificial intelligence systems that control the routing of the vehicles, batteries for powering electric vehicles, the chassis of the vehicles, the engines of petroleum-powered vehicles, and the motors of electric vehicles.

The analysis in this paper will primarily focus on how the interaction and competing meanings that the aforementioned social groups associate with AVs may cause the further assimilation of self-driving vehicles into the market to improve or worsen the overall environmental sustainability of the transportation industry.

Issues with the Current Regime

One large contributor to the collective pollution caused by conventional modes of personal transportation in the United States is the sheer number of automobiles which are on the road at any given point in time. In today's regime, the average car in the US spends more than 95 percent of total time parked (Bates & Leibling, 2012). While this fact does not directly contribute to automobile pollution, it does mean that Americans collectively own many more cars than is strictly necessary to meet transportation needs, assuming even distribution of ownership. This is likely due to the fact that although most people don't need to be driving their vehicle for the majority of the time that they own it, they do require consistent access to a vehicle for mobility purposes. This high-ownership, low-utilization phenomenon leads a 76% of Americans to drive alone to work, according to a Brookings analysis of 2016 US census data (Tomer, 2016), drastically increasing the number of individual vehicles on the road and in turn increasing the amount of greenhouse gasses emitted by vehicles on the average work day. By eliminating the need for an alert human driver, AV technology could significantly reduce the number of vehicles on the road at any point in time and encourage commuters to share cars without sacrificing freedom of movement.

Another environmental factor to current automobiles is fuel efficiency. While cars continue to become more and more fuel efficient with every year, rising from an average of 16 mpg in 1980 to 22.4 mpg in 2008 (Anderson, et al, 2010), cars still make a sizeable contribution to US greenhouse gas emissions. Even as gas mileage standards improve, a large disparity in the efficiency of cars still exists between highway and city driving, with highway miles per gallon (mpg) ratings substantially exceeding city mpg due to the stop-and-start nature of city driving. AVs can potentially alleviate this issue as well, as connected self-driving vehicles will be more adept at maintaining constant speeds and smoothly accelerating, even in city driving environments, than their human-driven counterparts.

However, it is possible that the arrival of autonomous vehicles will not be a purely positive development for the environmental impact of transportation. As AVs improve fuel economy and decrease the need for human drivers, a short-term increase in cost due to the initial expense of autonomous or semi-autonomous systems will be met with a medium-term decrease in cost as the pertinent technologies are iterated upon and improved, which will necessarily result in an increase in the demand for automobile mobility, ceteris paribus. With lower costs for using cars, it is possible that commuters who could otherwise choose more sustainable modes of transportation such as walking or bussing will choose to use personal vehicles, which could increase vehicle miles driven and counterbalance the aforementioned positive environmental impacts of self-driving vehicles.

Electric and Autonomous Vehicle Synergy

Drive train electrification and self-driving technology have long been viewed as synergistic technologies. This is due in part to Tesla's status as an industry leader in AV research, offering the most advanced consumer-available autopilot system currently on the market. The pairing of autonomous driving with electric power is not purely coincidental however, as many of the characteristics of the technologies make them directly complementary. Firstly, electric vehicles are far less mechanically complex than cars powered by internal combustion engines, meaning that the drive train can be more readily controlled by the signals that would come from an autonomous central computer (Underwood 2015).

One of the largest obstacles preventing electric vehicles (EVs) from further penetrating the personal transportation market is range anxiety, which stems from the fact that electric vehicles have finite battery capacities, and unlike traditional combustion-based vehicles, cannot quickly refuel if they run out of fuel far away from the user's home. Although much progress has been made toward mitigating this issue in the form of increased battery capacities and the expansion of charging infrastructure in major cities, range anxiety remains among the most influential factors preventing consumers from adopting electric transport en masse. Autonomous vehicle technology, especially when paired with a ridesharing system, is capable of mitigating range anxiety by utilizing the 95% of time a vehicle would otherwise be parked and unused to navigate to a charging station and refuel.

In a 2016 study with the University of Virginia, D. Chen et al analyze the synergy between shared autonomous vehicles and electric vehicle technology by simulating an agent-based model of a network of shared, autonomous, electric vehicles. In the paper, they argue that fleet-managed AVs relieve many of the issues that plague privately-owned electric vehicles by "managing range and charging activities based on real-time trip demand and established charging-station locations (Chen et al, 2016)." The simulation described in this study can be understood as an actor-network comprised of the shared, autonomous, electric vehicles (SAEVs), the companies operating fleets of those vehicles, the passengers using the vehicles for mobility, and the physical infrastructure enabling the operation of the fleet such as the roads and the charging stations. For such a fleet to even exist, a major shift in consumer opinion toward AVs would need to occur, as 61 percent of respondents to a 2018 Brookings survey stated that they would be unlikely to even ride in an autonomous vehicle (Brookings). This issue will not likely reach closure quickly, and for a system such as that of the study to emerge, multiple successful pilot programs would almost definitely be required to demonstrate the safety of the technology to prospective users. Another issue with constructing such a fleet of SAEVs is the interpretative flexibility of the passengers who would use it. It is likely that passengers would have a wide variety of priorities in terms of which features of such a fleet are important. Specific design decisions would need to be made regarding the sizes of ridesharing groups, and perhaps even options for solo rides, which for maximum efficiency would need to be coupled with chassis redesigns in order to accommodate solo riders without the need to waste seats. Alternatively, solo rides could be disallowed entirely, which would have the consequence of excluding a sizeable portion of the potential user base.

The simulation conducted by Chen et al constructs a 100-mile by 100-mile grid with roughly the same population density profile as Austin, Texas as the stage for its analysis, comprised of three zones corresponding to downtown, suburban, and exurban areas, each with differing densities and trip rates. The simulation then generates a grid of charging stations, followed by a fleet of SAEVs, with the fleet consisting of vehicles with a 200-mile range similar to the Chevrolet Bolt and Tesla Model 3. After simulating two 24-hour periods with probabilistically-determined trips, the study found that SAEV users would pay between 21 and 49 percent of the current rates charged by companies such as Uber and Lyft, or between $0.70 and $1.23 per mile, which is "competitive with AAA (2014) estimates of average costs of private vehicle ownership… suggesting that availability of a AAEV fleet can have significant effects on private vehicle use (and ownership) (Chen et al, 2016). The study concludes by arguing that in a scenario where automated electric charging is widely available, a fleet of shared, autonomous, electric vehicles would be able to serve 95.6 and 97.9 percent of all trips with average wait times between 7 and 10 minutes at a cost comparable to that of private vehicle ownership. This conclusion suggests that the combination of AV with EV technology in a shared transport regime would be effective in propelling both technologies toward widespread adoption, which would drastically increase travel efficiency in terms of total miles driven, reducing energy consumption overall, and by extension, emissions due to transport.

In a March 2017 study of the energy consumption possibilities of autonomous vehicles (EIA, 2017), focusing on a 15-year time horizon, the US EIA analyzed AVs by focusing on an actor-network including human and non-human actors such as the vehicles themselves, sensors (e.g. radar, LiDAR, and sonar), passengers, automotive companies, passengers, consumers, federal governmental agencies, and municipal governments. The study finds that the aggregate energy consumption effects of AVs are dependent on the balance between the positive environmental effects of increased lane throughput, accident prevention, eco-driving, vehicle light weighting, and drivetrain electrification and the negative environmental effects of increased vehicle demand due to increased passenger productivity and comfort, expansion of vehicle access for underserved groups such as the elderly, and reduced ride-sharing. A particularly interesting conclusion of this study involves the symbiosis of self-driving technology and electrification. Because vehicle systems in an autonomous vehicle would be directly controlled by computerized systems, electrification of the vehicle's drivetrain would give designers the ability to utilize drive- and brake-by-wire systems in the vehicle (Kalinowski, 2014). This means that as AVs move toward widespread adoption, there will likely be an incentive for car manufacturers to transition toward electric rather than combustion-based drivetrains, which would play a large part in shifting the United States' current transportation regime toward more environmentally sustainable practices.

Scenario Analysis

Although there is an established compatibility between electric and autonomous vehicle technology, the transition from gasoline-powered to electric vehicles will be gradual, as the charging infrastructure will need to be substantially expanded to support a widespread move toward electric vehicles. It is also possible that the near-inevitable transition toward autonomous transportation will not coincide with major growth in electric vehicles, either due to petroleum industry pressure or a lack of public support for widespread infrastructure changes. In this case, the environmental impact of widespread AVs is more ambiguous, as the dominant factor in the net direction of emissions effects will be in the demand effects on the number of total miles driven and the total number of vehicles in operation.

In a quantitative analysis at Vanderbilt University (2019), Y. Chen, et al create a model to "quantify system-wide fuel impacts of AVs in the United States (Chen et al 2019)." The main methodology of the study is to focus on the stock of vehicles, annual miles traveled, and fuel efficiency in an attempt to produce a range of predictions for possible effects on national fuel consumption in the US as the market share of autonomous vehicles grows over the time period 2019-2040. The study specifically avoids exact fuel consumption estimates, and instead opts for a factor-based approach whereby ranges of possible effects of a series of mechanisms such as platooning, crash avoidance, changing highway speeds, and changes in travel demand are forecasted in both partially-autonomous and fully-autonomous cases in highway and city environments.

While the researchers briefly allude to the potential of AVs to encourage the use of alternative fuels (i.e. electric power), the analysis does not focus on this element, instead assuming that gasoline will remain the dominant fuel source of personal transportation and examining the possible stock and behavior changes on vehicle miles traveled that could result from increasing AV market penetration. After expanding on the mechanisms underlying their model, the researchers conclude with the admission that the possible fuel consumption outcomes of AV technology range from a reduction of 45% in the optimistic case to an increase of 30% in the pessimistic case, adding that any vehicle-level fuel efficiency improvement could be offset or outweighed completely by travel behavior effects and increases in vehicle miles traveled. The group specifically emphasizes the need for intentional governmental policy initiatives that counteract the likely increases in transportation demand that will result from AVs. Overall, this study provides a clear argument that the rise of autonomous vehicles will deliver improvements in vehicle efficiency, but that the overall environmental effects will depend largely on the magnitude of demand increases due to increased access and lower cost for vehicle transportation, and that the on-balance environmental effects of AVs will be dependent on the ability of the government to effectively prevent those demand effects from increasing overall vehicle miles traveled.

A compilation of existing research by the US National Renewable Energy Laboratory (NREL, 2015) explored a series of possible scenarios involving the widespread adoption of autonomous vehicles, or lack thereof, in order to evaluate the different potential impacts on fuel usage. The study examines 8 different future scenarios for AV development, separating them into two groups: scenarios involving private ownership and low penetration, and scenarios involving shared ownership and high penetration. The underlying assumption of this grouping is that scenarios of widespread adoption of AV technology will be coupled with a shift of the US automobile regime toward shared use of vehicles, rather than private ownership. In the scenarios of low penetration and private ownership, which comprise scenarios one through three, the predicted net effects on total low-duty fuel demand range from -5% to +8%, implying that if autonomous vehicles do not reach a large share of the total transportation market, they will have a relatively neutral effect on the demand for fuel.

Alternatively, the scenarios which involve high penetration into the market (scenarios four through eight), the net effects range from -87% to +217% fuel consumption, representing drastically different outcomes depending on the specifics of the adoption of these vehicles. It should be noted that four out of the five high-penetration scenarios are predicted to reduce fuel consumption by 68% or more, while the single outlier scenario is predicted to increase consumption by 217%. The high-penetration, high fuel consumption scenario assumes that the shift toward a majority self-driving, shared vehicle model will be accompanied by the maximum plausible increase in travel demand, due both to decreased cost and increased accessibility.

Weighing all of these possible scenarios, the NREL concludes that the most likely outcome of high AV penetration into the market will be a substantial decrease in the use of fuel, with the caveat that demand effects could counteract or even outweigh these positive factors in the worst-case scenario.

Conclusion

Having established a decisive synergy between electric and autonomous vehicles, and having evaluated a series of future possibilities for AV adoption from the perspective of fuel demand, it is clear that there is a strong relationship between AV technology and environmental sustainability. However, the direction of this relationship is undetermined. Knowing that the arrival of AV technology will coincide with a likely increase in miles driven overall due to increased access for members of groups underserved by the current transportation industry, in the absence of counteracting factors the relationship of AV technology to environmental sustainability will be negative. Among the possible factors which would counterbalance the miles increase are whether or not AV technology spurs the widespread adoption of electric vehicles, whether drivers are willing to use a shared fleet of autonomous vehicles rather than instead of their own personal cars, and the overall fuel efficiency gain of improvements to routing, traffic congestion, and acceleration smoothing brought about by autonomous vehicles.

As previously stated, the sociotechnical arrangement around autonomous vehicle technology is far from stabilization. Currently, consumer opinion swings heavily against both AV technology and electric vehicle technology, mostly due to safety concerns in the case of AVs and mostly range anxiety and expense in the case of electric vehicles. In order to reach the most environmentally sustainable outcome, extensive research and development is required from battery manufacturers in order to reduce the currently considerable expense of batteries, which make up a large portion of the difference in price between electric and internal combustion vehicles, while also increasing battery capacity. Additionally, companies on the forefront of AV research such as Uber, Waymo, and Tesla must demonstrate that autonomous vehicles provide an appreciable benefit in safety over human driving, which will also require further research and development.

In the case of ridesharing, interpretative flexibility between groups of potential consumers will be a significant obstacle preventing a transition away from personal vehicle ownership. Because of AVs' established compatibility with ridesharing, the most sustainable outcome in terms of miles driven is a shared ownership model, however most drivers have an aversion to sharing vehicles with strangers. Because of this conflict between the need for efficiency and the need for consumer comfort, compromise will be necessary in order to produce an outcome which most stakeholders will accept.

Assuming one or more of the aforementioned positive developments is pursued in conjunction with the adoption of AVs, the overall environmental sustainability of the transportation industry will likely improve. Given the tremendous contribution that cars in the current transportation regime make to aggregate greenhouse gas emissions, and the established compatibility of autonomous vehicle technology with a series of positive factors for sustainability, a societal push toward the adoption of a combination of electric, autonomous, and shared vehicles is not only positive, but necessary to ensure that the contribution of transportation to the growing threat of climate change is substantially reduced.

References

Anderson, S., Fischer, C., Perry, I., & Sallee, J. (2010, September). Automobile fuel efficiency standards: impacts, efficiency, and alternatives. *NBER Working Paper Series.*

Bates, J. & Leibling, D. (2012, July). Spaced out, perspectives on parking policy. *RAC Foundation.*

Chen, T. D., Kockelman, K. M., & Hanna, J. P. (2016). Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions. Transportation Research Part A: Policy and Practice, 94, 243-254. https://www.sciencedirect.com/science/article/pii/S096585641630756X

Chen, Y., Gonder, J., Young, S., & Wood, E. (2019). Quantifying autonomous vehicles national fuel consumption impacts: A data-rich approach. Transportation Research Part A: Policy and Practice, 122, 134-145. https://www.osti.gov/servlets/purl/1409303.

Environmental Protection Agency (2017). U.S. transportation sector greenhouse gas emissions, 1990-2017. *Environmental Protection Agency.*

Fagnant, D. J. & Kockelman, K. (2015, July). Preparing a nation for autonomous vehicles: opportunities, obstacles, and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77,* 167-181. https://doi.org/10.1016/j.tra.2015.04.003.

Federal Highway Administration (2017, February). Traffic congestion and reliability: trends and advanced strategies for congestion mitigation. *U.S. Department of Transportation.*

Kalinowski, J., Drage, T., & Bräunl, T. (2014). Drive-By-Wire for an Autonomous Formula SAE Car. *IFAC Proceedings* Volumes, 47(3), 8457-8462. Retrieved from http://uamt.fei.stuba.sk/web/sites/subory/intranet/dokumentacia_konferencii/ifac2014/media/files/1156.pdf

Kane, M. (2019, January). US plug-in electric car sales charted: December 2018. *InsideEVs.* From https://insideevs.com/news/342380/us-plug-in-electric-car-sales-charted-december-2018/

Lee, J. & Kockelman, K. (2019, January). Energy implications of self-driving vehicles. *Energy Policy*. Retrieved from https://www.caee.utexas.edu/prof/kockelman/public_html/TRB19EnergyAndEmissions.pdf

McNew, L. (2014, October). Americans will waste $2.8 trillion on traffic by 2030 if gridlock persists. *INRIX & Centre for Economics and Business Research.*

National Highway Traffic Safety Administration (2012) Fatal Analysis Reporting System. *U.S. Department of Transportation.*

National Highway Traffic Safety Administration (2013) Traffic safety facts. *U.S. Department of Transportation.* DOT HS 811 753.

Sen, B., Noori, M., & Tatari, O. (2017). Will Corporate Average Fuel Economy (CAFE) Standard help? Modeling CAFE's impact on market share of electric vehicles. Energy Policy, 109, 279-287.

Singh, S. (2015, February). Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. (Traffic Safety Facts Crash•Stats. Report No. DOT HS 812 115). Washington, DC: National Highway Traffic Safety Administration

Tomer, A. (2017, October). America's commuting choices: 5 major takeaways from 2016 census data. *Brookings.*

Underwood, S. (2015). Automated, connected, and electric vehicle systems: expert forecast and roadmap for sustainable transportation. *Institute for Advanced Vehicle Systems, University of Michigan.* Retrieved from http://graham.umich.edu/media/files/LC-IA-ACE-Roadmap-Expert-Forecast-Underwood.pdf.

U.S. Energy Information Administration (2017, March). Study of the potential consumption impacts of connected and autonomous vehicles. *Independent Statistics & Analysis, U.S. Department of Energy*

U.S. National Renewable Energy Laboratory (2015, July). Autonomous vehicles have a wide range of possible energy impacts. *Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.*

West, D. (2018, July). Brookings survey finds only 21 percent willing to ride in a self-driving car. *Brookings.* Retrieved from https://www.brookings.edu/blog/techtank/2018/07/23/brookings-survey-finds-only-21-percent-willing-to-ride-in-a-self-driving-car/.

Zhang K., Batterman S. (2013, April). Air pollution and health risks due to vehicle traffic. *Sci. Total Environ*. 2013;450:307–316. doi: 10.1016/j.scitotenv.2013.01.074