Key Factors Influencing Autonomous Vehicles' Energy and Environmental Outcome

William R. Morrow III, Jeffery B. Greenblatt, Andrew Sturges, Samveg Saxena, Anand Gopal, Dev Millstein, Nihar Shah and Elisabeth A. Gilmore

Abstract Autonomous vehicles (AVs)—vehicles that operate without real-time human input—are a potentially disruptive technology. If widely adopted, there is the potential for significant impacts on the energy and environmental characteristics of the transportation sector. This paper provides an outline of key drivers likely to influence the magnitude and direction of these impacts. We identify three broad categories: vehicle characteristics, transportation network, and consumer choice. Optimistically, AVs could facilitate unprecedented levels of efficiency and radically reduce transportation sector energy and environmental impacts; on the other hand, consumer choices could result in a net increase in energy consumption and environmental impacts. As the technology matures and approaches market penetration, improved models of AV usage, especially consumer preferences, will facilitate the development of policies that promote reductions in energy consumption.

Keywords Environmental impacts · Energy efficiency · Autonomous vehicles

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Elisabeth A Gilmore: Deceased

W. R. Morrow III (✉) · J. B. Greenblatt · A. Sturges · S. Saxena ·
A. Gopal · D. Millstein · N. Shah
Lawrence Berkeley National Laboratory, 1 Cyclotron Road,
Berkeley, CA 94720, USA
e-mail: WRMorrow@lbl.gov

E. A. Gilmore
University of Maryland, 2101Van Munching Hall, College Park, MD 20742, USA

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1 Introduction

The nature of the transportation sector is the manifestation of a continuous evolution in vehicle designs, transportation system infrastructure, and the built environment with complex interactions between consumers[1] vehicle manufacturers, energy markets, policy makers, and urban planners. Although there are some instances of rapid vehicle technology deployment (e.g., seatbelts for passenger safety), the transportation sector's evolution is often slow. In the least, consumers, auto manufactures, and infrastructure usefulness function on different relevant time scales. Historically, consumers retained their vehicles until end of life; increasingly, consumers are switching vehicles frequently. Manufacturers require many years of sales to recoup investments made in new vehicle models. Most transportation infrastructure (i.e., roads, highways, and fuel systems) has multidecadal life span. Thus, a transportation sector's energy[2] consumption profile reflects its mix of legacy and emerging technologies utilized to satisfy transportation services.[3] In the U.S., the transportation sector's evolution has led to continued increases in energy consumption, as transportation service demands—namely vehicle size and power as well as aggregate vehicle miles traveled—have historically outpaced vehicle efficiency gains [1].

Currently, vehicle automation technology is being developed with the promise of increasing transportation safety. This development has the potential to eventually offer affordable autonomous vehicles[4] (AV) to consumers. Although AVs are gaining attention, and a few are currently being tested as of 2014 (e.g., Google's AV cars), widespread AV adoption could still be decades away or prove too complex or socially unacceptable and always remain on the horizon. However, if successful and socially acceptable, it is possible that transportation sectors could become dominated by AVs one day. A hopeful co-benefit of AVs is to reduce transportation energy consumption. For example, reducing accidents could have a positive impact on energy consumption by lessening congestion. However, would AV dominance necessarily reduce vehicle energy consumption? Moreover, the transportation sector can influence other sector's energy consumption patterns (e.g., transportation enabled sprawl into larger footprint buildings can affect commercial and residential building sector energy consumption, and vehicle and road materials

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[1] For simplicity, we define consumers as the people demanding transportation services such as passenger mobility and the movement of goods.

[2] In all cases, energy consumption will have an environmental impact. Currently this impact is through the release of emissions resulting in poor air quality and climate change, water consumption and altered quality, etc. Even in an "all renewable" or "low GHG emissions" future, energy consumption will require infrastructure investments. An "environmental impact" is implied where energy is mentioned in this chapter.

[3] Transportation service includes the movement of both passengers and freight.

[4] Autonomous vehicles (AVs) are defined here as vehicles that provide transportation services without the need for a human driver manually operating the vehicle in real time.

have manufacturing and industrial sectors life-cycle energy implications). Would AV dominance have a significant impact on economy-wide energy consumption? Finally, how confident are we in anticipating AV's energy outcomes?

In this paper, we identify a set of broad categories that would influence the energy consumption of a fully AV transportation sector: vehicle characteristics, transportation network and consumer choice. Within each category, we then discuss several key factors that could influence AV's energy outcomes along these dimensions and discuss the variability inherent to these factors. For a simplified discussion, we imagine a future in which AVs are fully adopted for all transportation services (i.e., providing close to 100 % of road-miles traveled) with a focus on the U.S system. Assuming full AV adoption implies that a cost-effective and socially acceptable technology deployment pathway took place. It is not our focus to discuss pathways and timing, cost and policy/legal considerations. We also remain agnostic about the fuel types and drivetrains that are employed for AVs. Thus, we are evaluating the factors that are specific to AV usage and do not comment on potential interactions with fuel/drivetrain options.

While a specific forecast will certainly be wrong, early stage anticipation of outcomes can help facilitate debate, policy, research, and ultimately steer AV development and deployment. Our intent is to interject into a rapidly growing AV debate that AVs' energy outcome is far from certain. We argue that because of the scale of the influence AVs could have on energy and the environment, both research and policy communities should anticipate developments along these key factors, and, to the degree possible, address potential concerns at an early stage.

2 Key Factors

Here, we group the factors that will influence future energy outcomes from widespread AV adoption into three main categories: vehicle characteristics, transportation network, and consumer choice. In Table 1, we present these factors in terms of increasing complexity of the factor being evaluated, uncertainty in the range of values, and potential influence on the resulting energy consumption.

We develop our list by drawing from the existing discussions on AVs. For instance, the Economist recently provided its readers with an overview of the potential benefits (e.g., increased safety, elderly and disabled passenger mobility, and fuel economy) as well as challenges (e.g., will consumers, insurers, and courts inhibit or usher in AVs?) associated with an AV future [2]. Eno Center for Transportation's report titled "Preparing a Nation for Autonomous Vehicles—Opportunities, Barriers, and Policy Recommendations", considers a range of AV adoption rates and then estimates the effect on safety and vehicle miles traveled (VMTs) [3]. AVs have also sparked public interest. For example, Brad Templeton's "Robot Cars" blog provides essays on AV topics including potential automobile design concepts such as right-sizing, greater fuel switching flexibility, and potential shift in consumer preferences leading to better urban planning, to name a few [4].

Table 1 Key factors influencing the energy outcomes of widespread AV adoption

Category	Key factors	
Vehicles characteristics	Weight	↓ *Increasing Complexity, Uncertainty & Influence*
	Performance[a]	
	Right-sizing[b]	
Transportation network	Communication[c]	
	Roadways	
Consumer choice	Services (passengers and freight)	
	Vehicle miles traveled	
	Communities (the build environment)	

[a] Used here to describe vehicle's cruising speed and acceleration (how quickly a vehicle reaches the cruising speed)

[b] Right-Sizing describes a concept of vehicles designs that are appropriate for the service they provide. For example, a single-passenger commuter vehicle could be designed, or "sized", for a single occupant, versus four passenger vehicles common in current commutes

[c] Data transmission that facilitates an AVs' control

Table 1 is not intended to be an exhaustive list of factors but instead to group key factors together and discuss the potential influence they might have on AV and transportation sector's energy consumption. While many of these factor's are commonly thought to offer advancements towards the future sustainability of societies, counterpoints are possible for many of these ideas. We caution that a fully AV transportation future might not resemble today's transportation sector, and the rules that have helped sector analysts estimate the effects from some of the more uncertain factors, such as consumer choice, may no longer apply.

2.1 Vehicles – Weight, Performance, and Right-Sizing

Weight and performance fundamentally affect a vehicle's energy consumption. All else equal, a lighter vehicle gently accelerating to a slower speed will consume less energy than a heavier vehicle rapidly accelerating to higher speeds. Vehicle engineers continuously seek to maximize vehicle performance and fuel economy. In addition, efforts are currently underway to reduce vehicle weights without compromising passenger safety. Characteristics of AVs, such as accident avoidance, could reduce the frequency and severity of accidents by quickly responding to surrounding traffic conditions and removing driver error, producing an inherently safer transportation system. Importantly, AVs accident avoidance could enable lighter vehicles and thereby reduce fuel consumption. Theoretically, a fully AV transportation system could eliminate accidents entirely. As the probability of accidents approaches zero, the burden of passenger protection could migrate from vehicle chassis and shells to autonomous controls. This might allow for radically lighter vehicles than currently possible in today's relative risky transportation system.

AV-enabled performance optimization could reduce energy consumption independent of weight reductions. Replacing humans with autonomous controls could remove sporadic acceleration and breaking which tend to lower a vehicle's energy consumption. AV passengers could be content with overall slower accelerations and speeds if that enabled less congestion. Conceptually, AV's could also minimize energy consumption by selecting the least energy intensive pathway to deliver passengers and goods in a more efficient manner than present routing systems.

Finally, individual AVs could in theory be coupled using communication systems—e.g. multiple smaller modular vehicles could operate as one unit. This could facilitate savings from weight-reduction by vehicles that are right-sized for the services they provide. For example, AVs could allow passengers to use vehicles designed for specific transportation services such as commuting versus a family camping trip. Right-sized single-occupancy commuter vehicles could also be much smaller and efficient than today's sedans. Apart from passenger vehicles, there may be potentially larger efficiency gains for delivery systems. Right-sized AV delivery vehicles could be substantially smaller and lighter if safely delivering goods, but not protecting humans, became the dominant design objective.

2.2 Transportation Network – Communication and Roadways

Although it is theoretically possible for AVs to function without external communication, energy benefits could come from communication, either between AVs (i.e., "vehicle-to-vehicle"), a regional network, or both. Communicating vehicle positions, relative speeds, and destinations could reduce accidents and congestion by safely synchronize groups of vehicles to reduce cascading effects[5] . This communication could also accommodate merging and exiting AVs. Both of these will have the effect of reducing individual vehicle energy consumption. There could also be additional vehicle energy savings through higher-speed traffic "platooning". Platooning shortens safe traveling distances between vehicles reducing net drag resistance.

A vehicle-to-regional communication could enable benefits in localized zones as well as system-wide. For example, system-wide energy savings benefits could be realized if vehicle-to-regional communication enables predictive management at heavy commuter times. This could minimize the energy intensive vehicle starting and stopping of the majority traffic flow direction. Additional system-wide energy savings benefit could be realized through regional communication networks optimizing aggregate flows of passengers and goods and allocating AVs appropriately across all potential routes. Theoretically, a fully

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[5] Cascading effects are the subsequent vehicle responses to sudden braking and or accelerations in vehicles preceding them.

AV transportation system could satisfy all transportation service demands at all times while minimizing system-wide net service time and energy consumption. However, this could require system-wide regional communication networks that could be data intensive and require large computational resources.

While communication could enhance system-level performance with minimal infrastructure changes, roadway infrastructure adapted to a fully AV transportation sector could tap into even greater system-wide energy savings throughout the larger built environment. Presently, when the majority of vehicles are moving in the same direction, the counter-flow lanes are under-utilized. Thus, aggregate AV flows could determine road lane and direction allocations in a dynamic and safe manner. Also, a right-sized AV stock would present even greater flexibility in allocating traffic flows and roadway utilization. These changes to roadway patterns, however, may require new infrastructure designs. At the city level, we would need to consider how to accommodate pedestrians and bicycles. At the high-speed highway level, AVs might require roadway designs that facilitate entering and exiting AVs, directionally dynamic roadway lanes and other modifications that facilitate continuous AV flows.

2.3 Consumer Choice – Services, VMTs, and Communities

Consumer choice has the largest degree of uncertainty. This category may also have the largest influence on AV's energy outcome through changes in the total demand for transportation service demands. At the highest level, AVs could increase the total number of consumers if transportation services are opened to those currently excluded due to age, disabilities, or other reasons. Similarly, if AVs allow goods to flow more freely, a larger quantity of goods could be purchased and shipped. For example, a currently homebound person could become an AV user to travel across town and then order a single forgotten item (e.g., reading glasses) for immediate delivery, thereby introducing two new transportation service demands. In addition to increasing the size of the consumer pool, the choices those consumers make (e.g., vehicles chosen, VMTs, and life-style choices) in response to new flexibilities presented by AVs could be a radical departure from current choices. We highlight the range of possible outcomes through two scenarios.

Consumer choices could lead to an increase in energy consumption where individual energy usage and travel distances facilitated by AVs outpace any gains in efficiency – a resource dystopian outcome. Freeing passenger's attention from driving responsibilities could lead to increased "luxuries" designed into vehicles. This could include some elements that are presently in vehicles, such as entertainment systems. It could also extend to activities that we already to a lesser degree conduct in our vehicles, such as personal grooming and consuming food. For example, we could prepare food in our vehicle necessitating additional electronic equipment. If passengers communicate value from mobile luxury, then AV manufactures could respond by producing vehicles with increasingly larger sizes, weights, and ancillary energy requirements for electronics and climate control. Given these luxuries, consumers could have an increasing personal value derived from "living" in vehicles and choose to live further apart or away from employment resulting in increased VMTs and a sprawling built environment.

On the other hand, consumer choice could lead to decreasing energy intensity. Here, we emphasize the role that AVs can play in reducing the resources used for the transportation system as well as achieving more sustainable communities and built environments (i.e., buildings, roads, vehicles, utility distribution systems, etc.)—a resource utopian outcome. Conceptually, AVs could enable highly optimized and efficient transportation systems that deliver passenger safely and quickly, minimizing time spent in vehicles. Right-sized vehicles with minimal luxuries could become the least-cost and most demanded AVs. Moreover, AVs could arrive exactly when and where they are needed as well as transferred independently to the next service demand. This could make personal vehicle ownership unnecessary by providing right-sized vehicles "on demand". Future built environments could then emphasize living space over residential parking garages and productivity over commercial parking lots. Finally, an optimized network offering a highly efficient transportation system could draw people closer, supporting urban development, and reducing overall net energy consumption.

3 Anticipating Energy Outcomes – Complexity, Uncertain, and Influence

While our current understanding of the size and relative influence of these factors precludes a detailed model, we present "back of the envelope" estimates of potential AV energy outcomes for our two scenarios. Our approach is to estimate the change in fuel economy from vehicle and network improvements and VMT from consumer choice. In our utopian scenario, the resulting primary energy consumption could decrease by roughly 80 %, all else equal. Here, we envision radically improved vehicle and system efficiencies effectively tripling miles-per-gallons over anticipated average U.S. light-duty vehicle (LDV) performance [5], and shared vehicles and shorter distances decreasing VMTs by 40 %. In our dystopian scenario, if larger vehicles increase miles-per-gallons by 25 %, and privately owned vehicles and longer distances increase VMTs by 40 %, then transportation's energy consumption would more than double. The span of these estimates reflects the inherent uncertainty in predicting the future. However, as presented in Table 1, the factors that comprise our estimate range in complexity, uncertainty, and influence. Evaluating these factors qualitatively can inform future research and policy needs.

Engineers have well established methods and tools for predicting vehicle energy savings. While vehicles are complex machines, physics and engineering principles can be used to accurately estimate a vehicle's energy consumption and the relative energy savings potential from weight reductions and AV modified performance or drive-cycles. However, anticipating how much weight reductions or performance modifications autonomous controls will enable is much less certain. Although transportation researchers are currently working on energy savings estimates for measures such as platooning, energy savings estimates for other measures, such as "smoothing" entire highways, are speculative or rely on extrapolations from platooning. Estimating these savings is mostly theoretical in the current absence of AV traffic only highways for measurement and experiments.

Energy savings from transportation networks designed for AVs are far less certain than those derived purely from vehicles designs. Vehicle-to-vehicle communication will almost certainly be a component of an AV transportation network and will most likely offer some energy savings. There are, however, fewer established modeling approaches to quantify these energy savings. Additionally, we have assumed a regional communication network capable of system-wide optimization. This level of deployment may prove too difficult for implementation and its benefits speculative. For example, we did not explicitly address the practicalities of algorithms and computational needs of this system. We also did not consider social or economic constraints, such as public oversight and budgetary pressures, nor ethical, legal or liability concerns that may further limit the application and optimization of the networks. Improvements to roadway infrastructure, which has long construction times and life spans, could also prove too costly or impractical to accommodate a moving target of rapidly changing AV designs and needs. Thus, quantifying the network benefits may be bounded by optimization approaches, but the details of the final system and the interactions with the existing infrastructure over time may greatly reduce the observed benefits.

Estimating consumer preferences is even more challenging as we have little experience or analogs for AV options. Our scenarios for consumer choice, however, highlight the potentially large influence of consumers on the magnitude and direction of energy consumption. However, we limit our estimates to the potential response through variations in VMT and vehicle efficiencies. While these variables are clearly influenced by consumer behavior, they do not encompass the range of preferences that may influence AV energy consumption (e.g. private vehicle ownership versus vehicles "on demand"). Social scientists could address much deeper questions of consumer motivation and choice.

4 Conclusions

If the technology is successful and AVs become the primary mode of transportation, a number of key factors will likely influence the final energy consumption. AVs could be inherently safer compared to human operated vehicles (or even accident-free) enabling vehicle weight reductions and associated energy savings through vehicle efficiency gains. Further vehicle energy savings could be achieved if AVs are right-sized and their performance optimized. AVs operating in a dynamic transportation network could leverage additional system-wide energy savings and potentially alter roadway infrastructure to achieve even greater energy savings. Moreover, consumer choices could result in game-changing social efficiencies if urban densities emerge supported by highly efficient city transportation networks. However, the potential efficiencies that AVs offer should not obscure the possibility of a far-less optimistic outcome. Vehicle and system-wide energy savings could be negated by consumers choosing new luxuries and urban sprawl.

At this early stage of AV development, researchers and policy makers should be aware of the magnitude of influence that these factors could have on energy futures and prioritize an AV research agenda. Addressing these factors, however, will require new modeling approaches and multi-disciplinary collaborations. Policy makers may also want to anticipate the key drivers to facilitate the development of policies that promote reductions in energy consumption. While evaluating the social benefits compared to the costs is beyond the scope of this paper, a net benefit could provide motivation for policies that promote full AV adoption.

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